

UNCLASSIFIED

AD NUMBER

AD884995

LIMITATION CHANGES

TO:

Approved for public release; distribution is unlimited.

FROM:

Distribution authorized to U.S. Gov't. agencies and their contractors;
Administrative/Operational Use; 11 MAY 1971.
Other requests shall be referred to Air Force Applications Technical Center, Washington, DC.

AUTHORITY

AFTAC ltr 1 May 1972

THIS PAGE IS UNCLASSIFIED

AD884995

AD No. _____
DDC FILE COPY

273

(2)

**A SEISMIC STUDY OF TRAVEL-TIME ANOMALIES,
NETWORK EFFECTS AND LOCATION TECHNIQUES
IN THE ALEUTIAN ISLANDS**

MAY 11, 1971

**Prepared For
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D. C.**

**By
E. F. Chiburis
Consultant to Seismic Data Laboratory
D. P. Racine
Seismic Data Laboratory**

**Under
Project VELA UNIFORM**



**Sponsored By
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Order No. 624**

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Chief, AFTAC.

DISCLAIMER NOTICE

THIS DOCUMENT IS THE BEST
QUALITY AVAILABLE.

COPY FURNISHED CONTAINED
A SIGNIFICANT NUMBER OF
PAGES WHICH DO NOT
REPRODUCE LEGIBLY.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified.)

1 ORIGINATING ACTIVITY (Corporate author)

TELETYPE GEOTECH
ALEXANDRIA, VIRGINIA

24 REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

25 GROUP

3 REPORT TITLE

A SEISMIC STUDY OF TRAVEL-TIME ANOMALIES,
NETWORK EFFECTS, AND LOCATION TECHNIQUES
IN THE ALEUTIAN ISLANDS

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific

5 AUTHOR(S) (Last name, first name, initial)

Chiburis, E.F.;
Racine, D.P.

6 REPORT DATE

May 11, 1971

7a TOTAL NO OF PAGES

131

7b NO OF PAGES

12

8a CONTRACT OR GRANT NO

F33657-70-C-0941

8b PROJECT NO

VELA T/0706

9a ORIGINATOR'S REPORT NUMBER(S)

273

9b OTHER REPORT NO'S (Any other numbers that may be assigned this report)

ARPA Order No. 624

ARPA Program Code No. 9F10

10 AVAILABILITY/LIMITATION NOTICES

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Chief, AETAC.

11 SUPPLEMENTARY NOTES

12 SPONSORING MILITARY ACTIVITY

Advanced Research Projects Agency
Nuclear Monitoring Research Office
Washington, D.C.

13 ABSTRACT

A study is made of a set of well-recorded Aleutian Islands earthquakes and the nuclear explosion LONG SHOT. Whereas past studies of travel-time anomalies and location errors have been based on seismic signals from explosions, the main object of the current study has been to extend our existing principles to seismic data from earthquakes. Using a selected teleseismic station network, travel-time anomalies were computed and various techniques applied to achieve location consistency across the entire region. Basically, the techniques involve deriving space functions for the observed station anomalies and imposing the following criteria for success: tight clusters of locations for each event made with network subsets, acceptably low standard deviations from the least-squares solutions, and reasonable station anomaly functions.

Using LONG SHOT as a bias control point, a set of segmented constant anomalies were derived for the network of stations used. Neglecting depth, the relative location accuracy is believed to be about 5 km; standard deviations of solutions generally were reduced to less than 100 sec, a value accepted as being due to reading and timing error. Compared with published locations, the events in the Rat Islands and Near Islands as a result of applying the technique shift 10-30 km southerly, and those in the Fox Islands and Andreanof Islands shift 10-20 km southerly.

To demonstrate the difficulties of locating events in the Aleutian Islands, well-distributed sub-networks of a 329-station network were used to locate LONG SHOT. The locations obtained, all of which would have been accepted as not unusual because of network coverage, exhibit errors as large as 45 km with two-quadrant networks and 160 km with single-quadrant networks. Travel-time anomalies computed from the various solutions have a range of more than 11 sec at station W4N1.

To verify the techniques used, a study is also made of a set of hypothetical events and station anomaly functions. It is shown that (1) even though a constant network is used and a constant anomaly is the only error, relative accuracy may suffer due to a network effect caused by the nonlinear travel-time/distance relationships; and (2) the techniques of functionalizing the station anomalies are valid and could be implemented as recommended for studies in selected regions.

14 KEY WORDS

Event Location
Location Bias
LONG SHOT

Unclassified

Security Classification

A SEISMIC STUDY OF TRAVEL-TIME ANOMALIES,
NETWORK EFFECTS AND LOCATION TECHNIQUES
IN THE ALEUTIAN ISLANDS

SEISMIC DATA LABORATORY REPORT No. 273

AFTAC Project No.:	VELA T/0706
Project Title:	Seismic Data Laboratory
ARPA Order No.:	624
ARPA Program Code No.:	9F10
Name of Contractor:	TELEDYNE GEOTECH
Contract No.:	F33657-70-C-0941
Date of Contract:	01 April 1970
Amount of Contract:	\$ 1,828,736
Contract Expiration Date:	30 June 1971
Project Manager:	Royal A. Hartenberger (703) 836-7647

P. O. Box 334, Alexandria, Virginia 22 317

↑
This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Chief, AFTAC.

att: 1/5 C

This research was supported by the Advanced Research Projects Agency, Nuclear Monitoring Research Office, under Project VELA-UNIFORM and accomplished under technical direction of the Air Force Technical Applications Center under Contract F33657-70-C-0941.

Neither the Advanced Research Projects Agency nor the Air Force Technical Applications Center will be responsible for information contained herein which may have been supplied by other organizations or contractors, and this document is subject to later revision as may be necessary.

ABSTRACT

A study is made of a set of well-recorded Aleutian Islands earthquakes and the nuclear explosion LONG SHOT. Whereas past studies of travel-time anomalies and location errors have been based on seismic signals from explosions, the main object of the current study has been to extend our working principles to seismic data from earthquakes. Using a selected teleseismic station network, travel-time anomalies were computed and various techniques applied to achieve location consistency across the entire region. Basically, the techniques involve deriving space functions for the observed station anomalies and imposing the following criteria for success: tight clusters of locations for each event made with network subsets, acceptably low standard deviations from the least-squares solutions, and reasonable station anomaly functions.

Using LONG SHOT as a bias control point, a set of segmented constant anomalies were derived for the network of stations used. Neglecting depth, the relative location accuracy is believed to be about 5 km; standard deviations of solutions generally were reduced to less than 0.25 sec, a value accepted as being due to reading and timing error. Compared with published locations, the events in the Rat Islands and Near Islands as a result of applying the technique shift 20-30 km southerly, and those in the Fox Islands and Andreanof Islands shift 10-20 km southerly.

To demonstrate the difficulties of locating events in the Aleutian Islands, well-distributed sub-networks of a 329-station network were used to locate LONG SHOT. The locations obtained, any of which would have been accepted as not unusual because of network coverage, exhibit errors as large as 45 km with two-quadrant networks and 160 km with single-quadrant networks; travel

time anomalies computed from the various solutions have a range of more than 11 sec at station NP-NT.

To verify the techniques used, a study is also made of a set of hypothetical events and station anomaly functions. It is shown that (1) even though a constant network is used and a constant anomaly is the only error, relative accuracy may suffer due to a network effect caused by the nonlinear travel-time/distance relationships; and (2) the techniques of functionalizing the station anomalies are valid and could be implemented as recommended for studies in selected regions.

TABLE OF CONTENTS

	Page No.
ABSTRACT	
INTRODUCTION	1
DESCRIPTION OF THE DATA	6
DETERMINATION OF TRAVEL-TIME ANOMALY	7
ERRORS IN LONG SHOT LOCATION USING DIFFERENT STATION NETWORKS	12
DETERMINATION OF ANOMALY FUNCTIONS	17
Selection of a constant network	17
Initial locations	18
LONG SHOT anomalies for corrections	19
Simple functional anomalies	20
Fox 1/LONG SHOT anomalies	22
FARN anomalies	23
Fiducial functional anomalies	24
Aleutian functional anomalies	26
Aleutian regional anomalies	28
SYNTHETIC EARTH STUDIES	30
Synthetic functional anomalies	31
Anomaly interpolation using synthetic data	38
Step-off technique	39
CONCLUSIONS	45
REFERENCES	46

LIST OF FIGURES

Figure Title	Figure No.
Geographic location map of selected Aleutian Island events. Numbers adjacent to locations are NOS reported depths.	1
Anomalies computed from NOS hypocenters for station NP-NT.	2a
Anomalies computed from NOS hypocenters for station NUR.	2b
Anomalies vs distance for two LASA subarrays for northwesterly events.	3
Anomalies computed from adjusted hypocenters for station NP-NT.	4a
Anomalies computed from adjusted hypocenters for station NUR.	4b
LONG SHOT location errors using two-quadrant networks.	5
LONG SHOT location errors using single-quadrant networks.	6
LONG SHOT location errors using four-quadrant, 32-station networks composed of every tenth station selected by increasing azimuth.	7
LONG SHOT anomalies as a function of azimuth.	8
LONG SHOT location errors using four-quadrant, 32-station networks composed of every tenth station selected by increasing distance.	9
LONG SHOT zero-mean error distribution computed from known location.	10a

LIST OF FIGURES (Cont'd.)

Figure Title	Figure No.
LONG SHOT zero-mean least-squares error distribution computed from 329-station solution.	10b
Geographic location map of 17 selected events.	11
Location shifts for four networks obtained without anomaly corrections.	12
Location shifts for four networks obtained by applying LONG SHOT anomalies.	13
Determination of simple functional anomalies.	14a
Determination of simple functional anomalies.	14b
Location shifts for four networks obtained by applying simple functional anomalies.	15
Determination of FOX-1/LONG SHOT functional anomalies.	16a
Determination of FOX-1/LONG SHOT functional anomalies.	16b
Location shifts for four networks obtained by applying FOX-1/LONG SHOT functional anomalies.	17
Determination of anomalies using Fox, Andreanof, Rat, and Near (FARN) constraining events.	18a
Determination of anomalies using Fox, Andreanof, Rat, and Near (FARN) constraining events.	18b
Location shifts for four networks obtained by applying FARN (see text) anomalies.	19
Functional anomalies determined from fiducial LONG SHOT location.	20a
Functional anomalies determined from fiducial LONG SHOT location.	20b

LIST OF FIGURES (Cont'd.)

Figure Title	Figure No.
Location shifts for four networks obtained by applying fiducial LONG SHOT functional anomalies.	21
Anomalies computed from "best estimate" epicenters as determined using fiducial functional anomalies.	22a
Anomalies computed from "best estimate" epicenters as determined using fiducial functional anomalies.	22b
Determination of Aleutian functional anomalies.	23a
Determination of Aleutian functional anomalies.	23b
Location shifts for four networks using Aleutian functional anomalies.	24
Regional anomalies for Aleutian Islands events.	25a
Regional anomalies for Aleutian Islands events.	25b
Location shifts of hypothetical events due to applied random errors ($\sigma = 0.25$ sec).	26
Contrived functional anomalies (Syn-1) using synthetic data.	27a
Contrived functional anomalies (Syn-1) using synthetic data.	27b
Location shifts using theoretical arrival times with random errors and Syn-1 anomalies as earth-model errors.	28
Location shifts using theoretical arrival times with LONG SHOT anomalies as earth-model errors.	29
Vector addition for resultant location shifts.	30
Location shifts using theoretical arrival times with random errors and Syn-1 anomalies as earth-model errors plus LONG SHOT anomalies as corrections.	31

LIST OF FIGURES (Cont'd.)

Figure Title	Figure No.
Linear functional anomalies determined from two deliberately mislocated events plus LONG SHOT.	32a
Linear functional anomalies determined from two deliberately mislocated events plus LONG SHOT.	32b
Comparison of least-squares solution errors with contrived functional anomalies at three stations.	33
Location shifts obtained by applying functional anomalies shown in Figure 33.	34
Bias adjustment relation for determining location errors shown in Figure 34.	35

LIST OF TABLES

Table Title	Table No.
Hypocenter Information of 110 Selected Aleutian Islands Events	I
The Following Events Were Outside the Geographic Region Used in This Study	Ib
The Following Nine Events Were Set Aside for a Special Study at a Later Date.	Ic
Initial Teleseismic Network, Distances and Azimuths are from LONG SHOT.	II
Travel-Time Anomalies at NP-NT Computed from Various LONG SHOT Seismic Solutions.	III
Selected Arrival-Time Discrepancies Greater than 1.0 Sec (SDL- NOS)	IV
Definition of Network Subsets and Event Set	V
Location Shifts, Standard Deviations (σ), Clustering Effect (Shifts from the Mean) Obtained Without Anomaly Corrections	VI
LONG SHOT Anomalies for Fourteen Stations Relative to UBO	VII
Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained by Applying LONG SHOT anomalies	VIII
Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained by Applying Simple Functional Anomalies	IX
Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained by Applying Fox-1/LONG SHOT Functional Anomalies	X
Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained by Applying FARN Functional Anomalies	XI

LIST OF TABLES (Cont'd.)

Table Title	Table No.
Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained by Applying Fiducial Functional Anomalies	XII
Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained by Applying Aleutian Functional Anomalies	XIII
Final Best-Estimates of Event Set Located with Aleutian Functional Anomalies	XIV
Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained by Applying Regional Anomalies	XV
Event Parameters for Eleven Hypothetical Epicenters plus LONG SHOT	XVI
Set of Random Errors Applied to Theoretical Arrival Times	XVII
Location Results with Synthetic Earth-Model	XVIII
Absolute and Relative (to LONG SHOT) Location Errors for Hypothetical Events Using Network 1 and Synthetic Earth-Model.	XIX
Absolute and Relative (to LONG SHOT) Location Errors for Hypothetical Events Using Network 3 and Synthetic Earth-Model	XX
Average Location Errors Using LONG SHOT Anomalies with Synthetic Earth-Model	XXI
Average Location Shifts of Mean Epicenter, Standard Deviations (σ), and Clustering Effect Using LONG SHOT Anomalies with Synthetic Earth-Model	XXII
Adjusted Location Shifts Relative to Deliberately Mislocated Calibration Events	XXIII
Set of Least-Squares Errors Applied in Step-Off Technique and Resultant Standard Deviations	XXIV

INTRODUCTION

The main purpose of the present study is to apply to earthquakes those techniques known to be valid for accurately locating underground explosions within a small region using travel-time anomalies and teleseismic networks. Additionally, we hope to demonstrate techniques for extending the region over which functional station anomalies can be derived so as to provide more accurate locations than those obtained from simple least-squares schemes.

Heretofore, most seismic studies dealing with travel-times, location accuracies, and "station corrections" have used explosions to provide the event data set, because only then can one be certain of the hypocenter and, hence, of actual travel times, origin times, station anomalies, and the effects of an inadequate earth model. Such studies could meaningfully investigate time deviations on the order of 0.2-0.3 sec. Should one include earthquakes in the data set, conclusions regarding location accuracy and travel-time anomaly stability from one region to another always remain in question. This stems from the fact that errors in the location of an event assumed correct can produce errors 10-20 times the size of the time anomaly or of the anomaly change one is trying to observe (Chiburis and Dean, 1965; Chiburis, 1966).

Earthquakes have been used generally to obtain first-order effects of inhomogeneity, principally in the vertical velocity distribution of the earth compared to a standard earth model. Two such models are presently in common use: the Herrin (1968) model and the classical Jeffreys-Bullen model. A number of other models have been proposed (e.g., Archambeau et al., 1969) to provide finer details in the velocity distribution usually emphasizing

one or more low-velocity layers or transition zones not included in the Herrin and Jeffreys-Bullen models.

It is now clear that even these improved models are inadequate to give time-distance relations sufficiently accurate for locating large events much better than 20-25 km on the average. For small events, and correspondingly larger reading errors, the location errors can easily be 50 km or more.

Among others, Chiburis and Ahner (1970) pointed out, that the probable causes of the time anomalies are due to unknown lateral inhomogeneities in the mantle (all the way down to the core) and to complexities in the upper mantle and crust in the vicinity of the recording stations. It is doubtful that we will ever be able to devise a three-dimensional world model accurate enough to account for observed anomalies. However, in special cases one does not need a completely accurate model simply in order to locate events: anomalies can be determined from an explosion with known location and applied to subsequently recorded explosions in the same region. In this way, locations can be obtained with an absolute accuracy of 2-3 km (Chiburis, 1968). In fact, the exact location of the calibration event is immaterial; the accuracy of other events relative to it remains the same (Chiburis and Ahner, 1970). As a result of doing this for many regions, valuable information about the spatial patterns of event occurrence and the distribution of energy release could be provided. Most important, perhaps, is that location consistency among many events could be achieved, region by region, with the result that fewer events would have to be specially analyzed or would have to be excluded from bulletins simply because of poor time fits; furthermore, those events included would display significantly smaller station time errors. That such results are achievable when locating explosions has been demonstrated by

(among others) Chiburis (1968) and Chiburis and Ahner (1969) and (1970).

However, if earthquakes are excluded from analysis of location techniques and of model inhomogeneities, the number of regions available for study is severely limited and the results are apt to be less general. Also, explosions are usually detonated in such widely separated regions that the large variations observed in the anomalies between regions sometimes cannot be assessed. Since anomalies at a given station are known to change significantly over epicentral distances of several hundred kilometers, it is almost certainly invalid to determine anomalies from two regions a thousand kilometers or more apart, linearly interpolate between them, and hence obtain anomalies having any significance for understanding mantle inhomogeneities.

The principal difficulty with using earthquakes is that the determination of a travel-time anomaly requires an event location in space: latitude, longitude, and depth. Knowledge of the origin time is unnecessary. Although several event lists are available which provide hypocenters from which anomalies can be calculated for any network, the location parameters have been determined with sets of stations differing in number, in kind, and in reliability and quality of recording; and with widely different earth models. Thus with such an event set, the station anomalies computed are usually not consistent, even for earthquakes occurring in a single region; for earthquakes occurring in adjacent regions, the anomalies agree hardly at all. For explosions, reproducibility has been verified many times in several different regions (e.g., Chiburis and Ahner, 1970). There is no known reason (other than mislocation) why earthquakes should yield inconsistent anomalies, but explosions consistent ones.

However, a study of earthquake anomalies need not be deterred

if one is aware of the effects that mislocations can produce, and if the conclusions drawn are understood in that context. The objectives of the present study are: (1) to demonstrate that location and anomaly consistency can be achieved despite mislocation; and (2) to gain improvement in the relative locations of earthquakes throughout the Aleutian Islands region. Our criteria for success are location and anomaly consistency.

By location consistency, we mean that an event location obtained with a well-distributed network must agree within 5 km with the locations obtained with well-distributed subsets of the initial network. It must also be true that the least-squares time residuals of the several network solutions for the event reduce to levels generally accepted as being due to reading and timing error.

By anomaly consistency, we mean that the anomalies at a station must change across the Aleutian Islands in a physically plausible way, and that the set of anomaly functions derived for a network must produce location consistency.

The sequence of steps through which the report progresses to achieve the desired result is as follows. First, it is demonstrated that the location errors obtained by using different networks vary widely in magnitude and direction when locating the LONG SHOT explosion in the Aleutian Islands.

Therefore, a constant network is selected to locate a set of events across the Aleutians by (1) using no anomalies; (2) using the LONG SHOT anomalies; (3) using a linear anomaly function for each station (based on the reported locations); (4) using a linear anomaly function doubly constrained by an earthquake in the Fox Islands and the LONG SHOT explosion; (5) using a segmented linear anomaly function constrained by four events equally spaced.

across the Aleutians; and (6) repeating the last step but translating the function to remove the observed LONG SHOT bias.

Finally, instead of allowing the anomalies to vary continuously between constants, the anomaly function is assigned either two or three constant values across the entire Aleutians. Each of the steps, increasingly more complex, provides for some improvement in location consistency and all are presented to illustrate the method of analysis for a region as large as the Aleutian Islands.

In order to verify the results obtained above, a set of synthetic data for a hypothetical earth model is analyzed; it is shown that the same order of consistency is achieved when the technique is applied to the synthetic data as it was to the real data.

DESCRIPTION OF THE DATA

A set of well-recorded earthquakes from the Aleutian Islands region, which includes the Fox Islands, Andreanof Islands, Rat Islands, and Near Islands, was selected to form our data base. The event set (Table I) is composed of 108 earthquakes and two explosions ranging in magnitude from 4.3 to 6.5. The earthquake parameters given under the "NOS" column are those reported on the National Ocean Survey (NOS) Preliminary Determination of Epicenters cards. The location parameters of LONG SHOT, an underground nuclear explosion on Amchitka Island in the Rat Islands, are those released by the Atomic Energy Commission. The location parameters of FLEXBAG, an underwater explosion detonated about 65 km southwest of Amchitka Island (Chiburis and Ahner, 1969, for a seismic analysis), are those reported by Kos and Kennedy (1969). A plot of the epicenters is shown in Figure 1.

A teleseismic network of 54 stations, well distributed in distance and azimuth, was selected (Table II); of these, 18 are World Wide Standard Seismic Stations (WWSS), 28 are Long Range Seismic Measurement (LRSM) stations, four are Geneva-type Observatories, and four are F-ring stations at the Large Aperture Seismic Array (LASA) in Montana. Arrival times were read for those events recorded at the LRSM stations and observatories; arrival times for the WWSS stations were taken from the Earthquake Data Reports (EDR) published by NOS.

HYPOCENTER INFORMATION OF 110 SELECTED ALEUTIAN ISLANDS EVENTS

pH Qualities: (1) Depth well observed, (2) probably pH, Poor, (3) No Observation.

... 2.4. 1:

1157. FROM VOS
Location to
Adjusted Location

[illegible]

TABLE 1b

• THE FOLLOWING EVENTS WERE OUTSIDE THE GEOGRAPHIC REGION USED IN THIS STUDY

Event Number	Date	Region	SOS			Adjusted			Number of Reporting Stations	Depth km	Quality	SHIP FROM NOS	
			Latitude	Longitude	M	Latitude	Longitude	km				Location to Adjusted location	Azimuth
15	18 May 68	Fox	53.784N	168.318W	4.5	53.696N	168.361W	120	36		1	Distance km	190.2
16	04 Dec 65	Fox	51.260N	170.610W	5.5	51.225N	170.706W	55	13		1	239.6	
17	14 Jan 68	Fox	52.740N	171.230W	5.5	52.681N	171.294W	30	92		1	7.90	213.4
18	07 Aug 66	Fox	50.580N	171.330W	6.5	50.571N	171.338W	39	88		1	1.15	211.9
19	27 Oct 66	Fox	53.597N	171.410W	4.5	53.501N	171.452W	201	24		1	11.40	198.1
21	11 Nov 68	And	52.820N	175.017W	4.8	52.754N	175.053W	47	39		1	7.68	197.0
29	21 Feb 68	And	51.380N	176.000W	5.2	51.321N	176.087W	225	82		1	8.93	222.9
34	11 Dec 66	And	52.940N	176.130W	5.2	52.814N	176.233W	15	29		1	15.62	206.5
36	11 Dec 66	And	52.140N	177.260W	5.4	52.044N	177.233W	250	43		1	10.82	170.3
43	10 Mar 68	And	52.860N	177.620W	5.3	52.776N	177.624W	150	36		1	9.33	181.8
44	14 Dec 66	And	52.176N	178.543W	4.6	52.127N	178.493W	170	34		1	6.70	181.3
49	13 Mar 68	And	52.078N	179.949W	5.5	52.072N	179.947W	150	78		1	0.97	165.8
61	11 Aug 68	Rat	52.041N	179.5011	4.6	52.014N	179.5561	150	29		1	4.80	27.4
63	11 Dec 68	Rat	52.080N	178.3301	4.5	52.230N	178.421	175	18		1	2.10	51.9
67	05 Aug 67	Rat	52.215N	178.3481	4.7	52.164N	178.4021	110	24		1	6.76	145.3
73	14 Oct 68	Rat	52.050N	178.1701	5.2	52.030N	178.2651	140	28		1	6.92	108.7
77	11 Mar 68	Rat	50.110N	178.2501	6.3	50.104N	178.2291	30	74		1	1.69	245.5
78	01 Oct 65	Rat	50.640N	177.3901	5.1	50.702N	177.4911	40	19		1	9.97	45.8
81	06 Dec 65	Rat	50.616N	177.3891	5.1	50.649N	177.4561	45	37		1	5.69	55.4
82	25 Oct 68	Rat	51.070N	175.9701	6.0	51.053N	175.9551	40	43		1	3.17	199.3
87	02 Jan 66	Rat	51.080N	175.9701	4.7	51.197N	174.5501	45	33		1	14.50	334.2
97	26 Feb 68	Near	51.080N	174.6401	4.7								

TABLE 1c

•• THE FOLLOWING NINE EVENTS WERE SET ASIDE FOR A SPECIAL STUDY AT A LATER DATE.

Event Number	Date	Region	SOS			Adjusted			Number of Reporting Stations	Depth km	Quality	SHIP FROM NOS	
			Latitude	Longitude	M	Latitude	Longitude	km				Location to Adjusted location	Azimuth
1	07 Nov 68	Fox	53.472N	165.717W	4.7	53.604N	165.760W	15	36		1	18.78	189.3
52	11 Sep 68	And	50.364N	175.958N	4.7	50.348N	176.034W	30	30		1	5.41	255.4
11	05 Nov 68	And	52.066N	176.711W	4.5	52.511N	176.910W	170	18		1	1.81	231.6
68	08 Nov 67	Rat	51.030N	178.7001	4.3	51.119N	178.6901	35	17		1	9.99	355.9
69	08 Nov 67	Rat	51.050N	178.5701	4.2	51.028N	178.5551	40	31		1	1.66	204.0
70	08 Nov 67	Rat	51.120N	178.5201	5.3	51.084N	178.5091	20	21		1	4.03	191.2
71	08 Nov 67	Rat	51.070N	178.4201	5.2	51.053N	178.4151	20	54		1	2.46	134.4
72	08 Nov 67	Rat	51.140N	178.4201	4.6	51.122N	178.4361	40	28		1	2.29	150.1
92	11 Nov 65	Rat	51.690N	176.2201	5.0	51.472N	175.5681	45	12		1	5.46	232.3

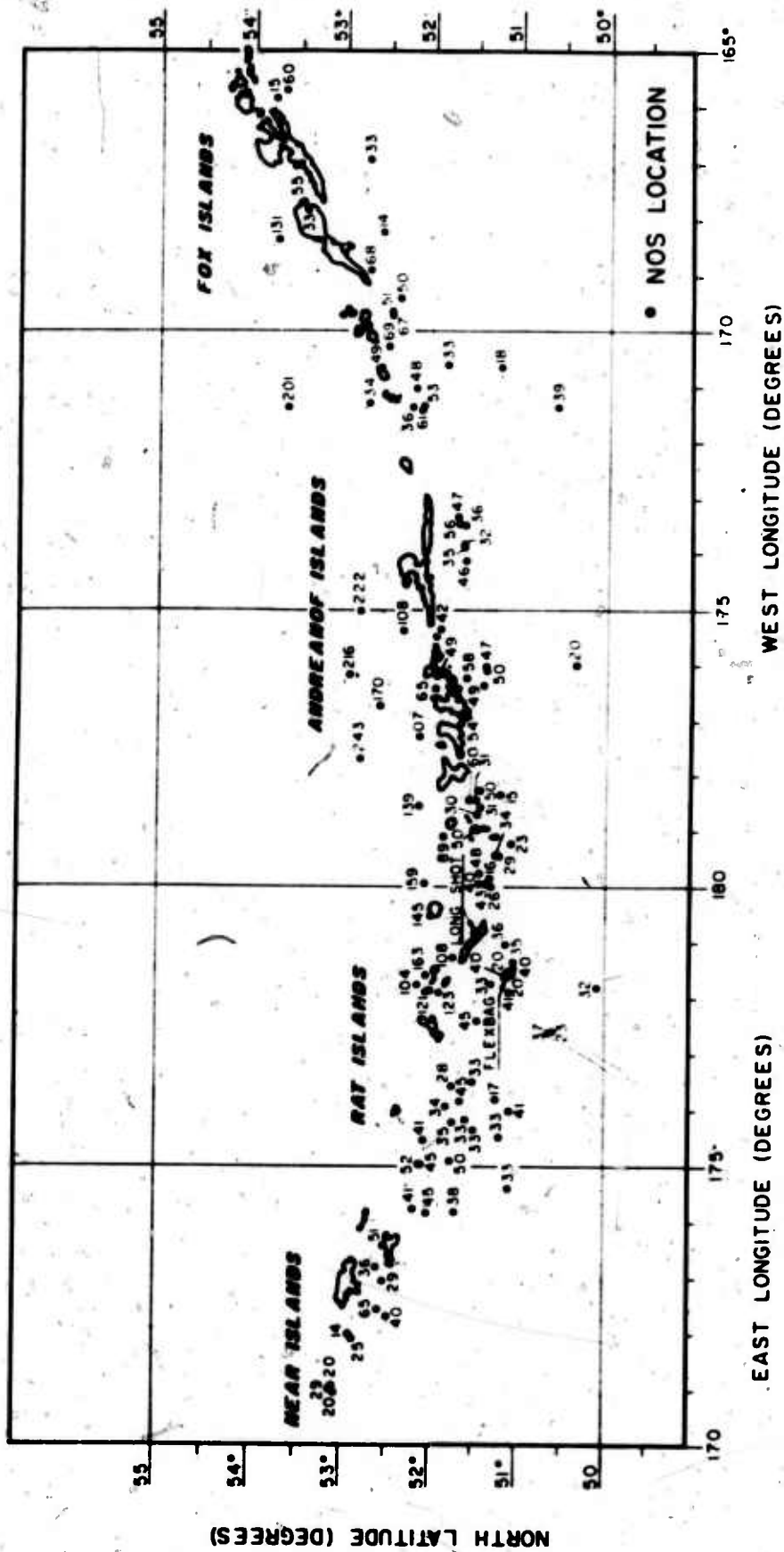


Figure 1. Geographic location map of selected Aleutian Island events. Numbers adjacent to locations are NOS reported depths.

DETERMINATION OF TRAVEL-TIME ANOMALY

As used in this report, the travel-time anomaly at station i relative to station j is defined as

$$A_{ij} = T_i - T_j - H_i + H_j$$

where T is observed arrival time and H is the travel time predicted from some established models. This definition has been used previously (e.g., Chiburis and Dean, 1965; Chiburis, 1966, 1968). In discussing travel time anomalies for a given network of stations, we refer travel times at all stations to that of a given station of the network. In other words, i varies and j remains constant.

Travel-time anomalies were computed using the Herrin (1968) tables for all the events in Table I and for those stations in Table II recording the events. Initially, the input latitudes, longitudes, and depths, necessary for calculating the predicted times, were those in Table I reported by NOS.

Plots of the anomalies for two selected stations relative to UBO are shown in Figures 2a and 2b as a function of longitude across the Aleutians. No implication is made as to the longitude parameter being of significance; it is mere convenience.

The variability observed in Figures 2a and 2b is far greater than expected: the anomalies are known to change as a function of event position, but not in the erratic manner shown. If the results in these two Figures were representative of actual anomaly profiles, the problem of calibrating seismic regions to the degree necessary for accurate location work would be almost impossible.

If it is assumed that the station anomalies are reasonably constant within a region, that they change only slowly if at all

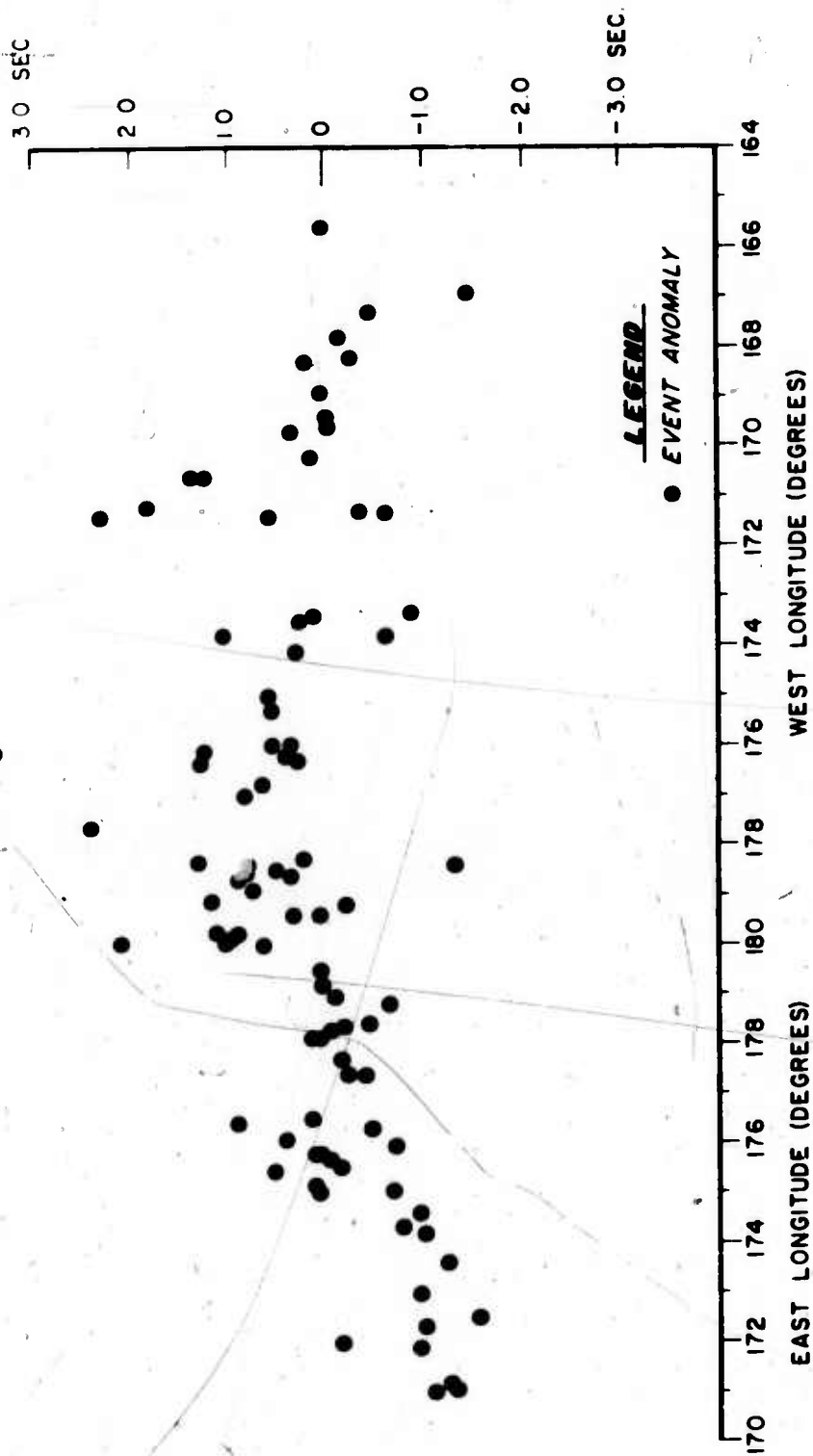


Figure 2a. ² Anomalies computed from NOS hypocenters for station NP-NT.

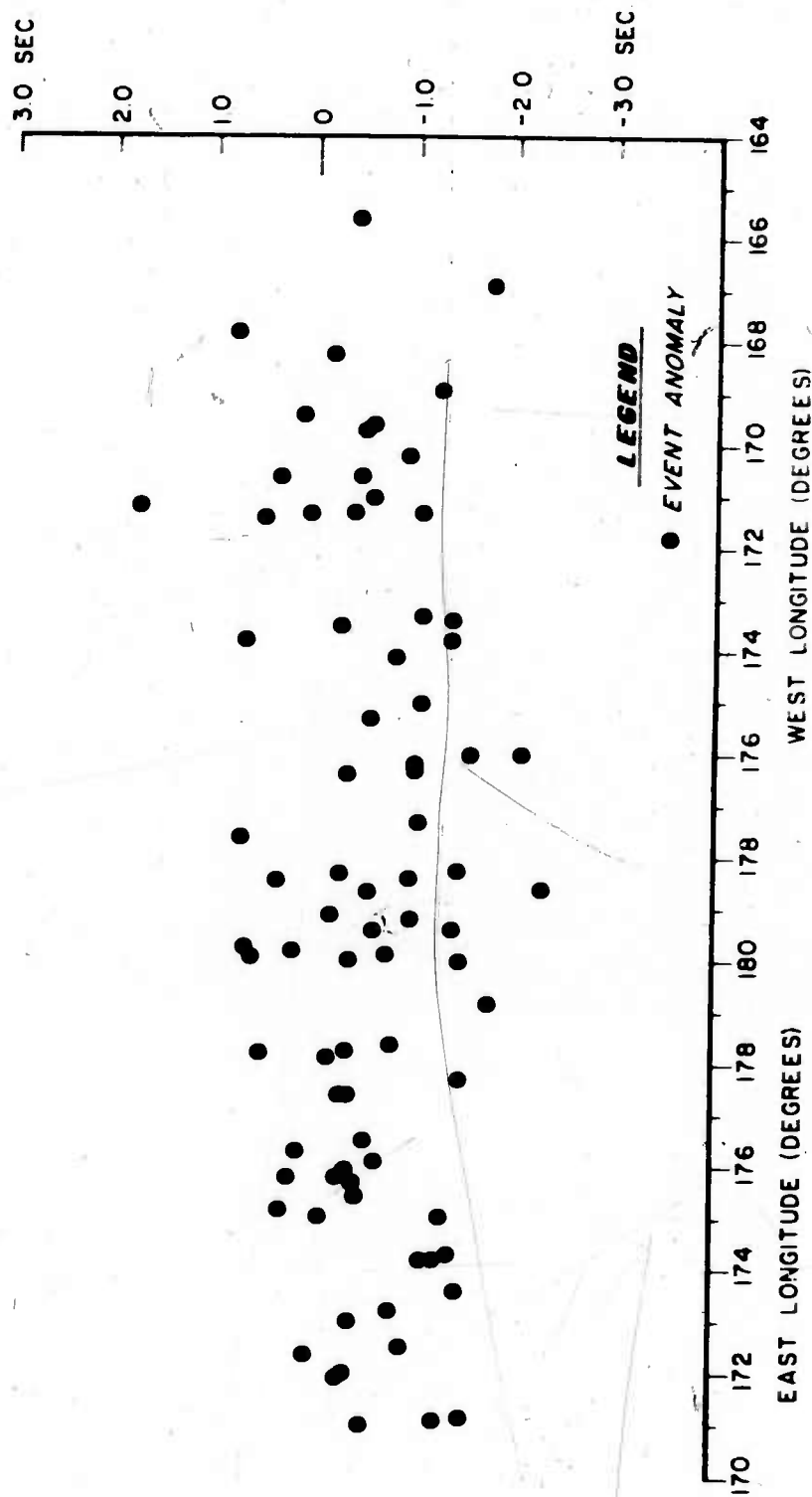


Figure 2b. Anomalies computed from NOS hypocenters for station NHR.

from one region to an adjacent one, and that the arrival times are read correctly to within 0.25 sec, the observed erratic behavior of the anomalies can be attributed only to mislocation of the hypocenter from which travel-times are computed.

It is well established that the anomalies for a station pair separated by a hundred kilometers or less computed from events in a particular region are constant, and that the anomalies vary slowly between adjacent regions (Chiburis and Dean, 1965; Chiburis 1966, 1968; Chiburis and Ahner, 1969, 1970). For example, in Figure 3 the anomalies at stations F4 and E2, relative to station A0 at the Large Aperture Seismic Array (LASA) in Montana, are plotted as a function of epicentral distance for events arriving along a northwesterly azimuth. In this figure, the anomalies are virtually constant (within about 0.1 sec) for a particular distance window (anomaly region) and vary smoothly from one region to the next. The effect of any event mislocation in this example would be minimal for the stations used because of the small distances to the reference station A0 (97 km for F4 and 69 km for E2) and this fact contributes to the consistency.

That the mislocation effect in computing the anomaly is a function of station pair separation has been discussed by Chiburis and Dean (1965) and by Chiburis 1966. In the latter study it was shown that the maximum anomaly error δA in seconds can be approximated by

$$\delta A \approx \frac{a \cdot \delta r}{\Delta^2} T$$

where a is the distance in kilometers separating the station and its reference, δr is the event location error vector in km, T is

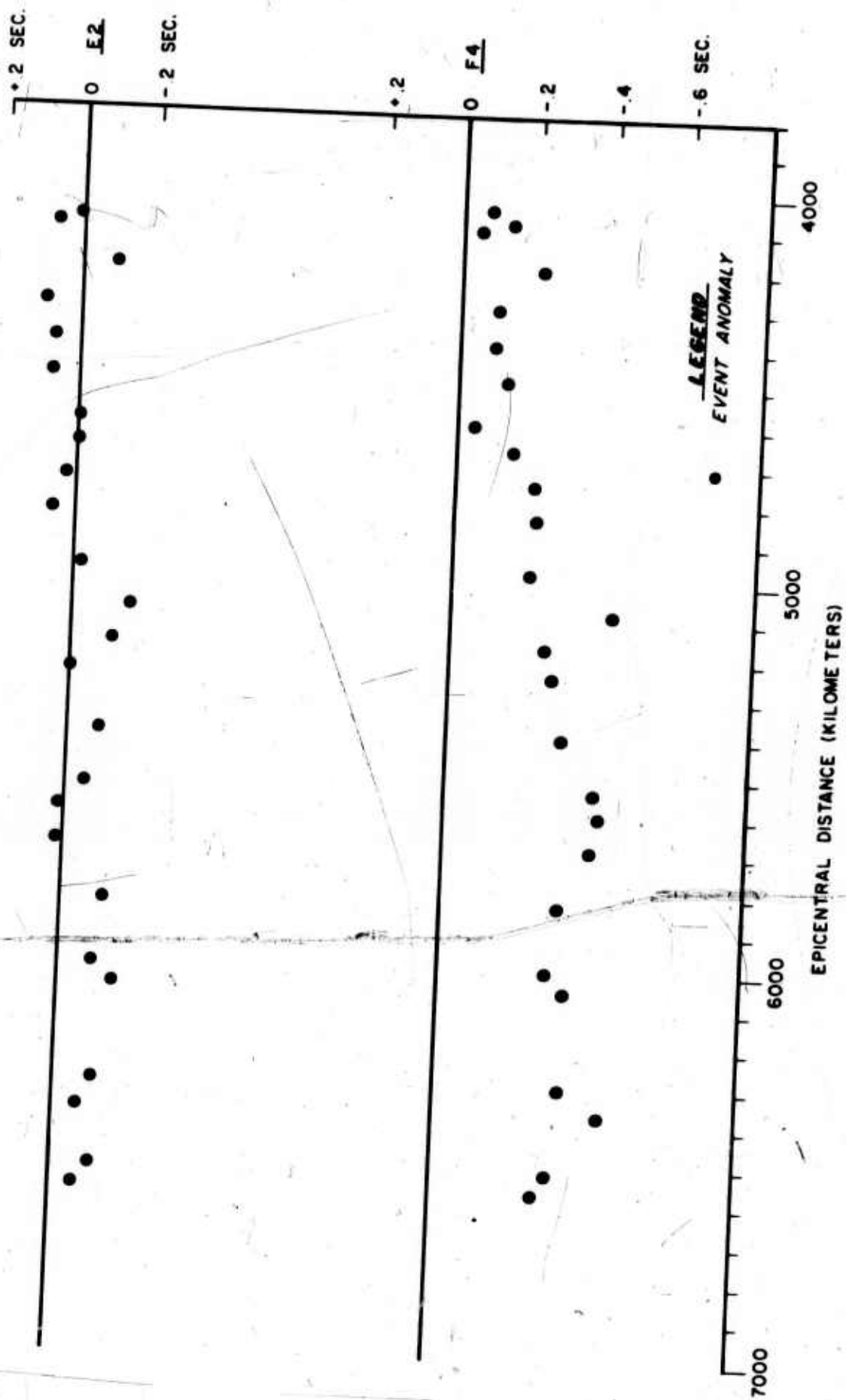


Figure 3. Anomalies vs distance for two LASA subarrays for north-westerly events.

the travel time in seconds, and Δ is the epicentral distance in km to the station pair. Therefore, if an event at a distance of 5,000 km is mislocated by 50 km, the errors in the computed anomalies for F4 and E2 would only be about 0.10 sec and 0.07 sec respectively. On the other hand, if the station-pair separation is 4,000 km, as is the case for NP-NT and UBO in Figure 2, the anomaly error would be about 4 sec. Clearly, even smaller location errors (on the order of 10-20 km) in the proper direction can explain quite large disagreements in the anomalies; such errors are the probable causes of the observed anomaly inconsistencies.

Before the anomaly errors due to epicenter mislocation can be properly assessed, the depths of the events must be known as well as possible. The depths resulting from an unrestrained least-squares solution of P arrival times, without corrections for travel-time anomalies, are known to have an average error of 75 km or more in some regions (Chiburis and Ahner, 1970). Such errors are far too large to permit a sensible determination of travel-time anomaly. The only known way to determine depth unambiguously is to identify the phase pP and restrain the least-squares solution. The selection of pP on an event seismogram recorded at a single station is highly subjective, principally because of signal-generated noise in the P coda and because of energy from a multitude of other phases. However, if a suite of seismograms recorded at different stations which are widely separated in distance and azimuth is aligned on the P wave, time-distance relationships of coherent energy can usually be correlated with distinct phases. Therefore, 110 events in Table I were analyzed in this way. The maximum disagreement with the NOS reported depths in the event set is about 50 km. Although depth errors by themselves do not produce large anomaly changes, the differences in epicenters, had the events been located with restrained depths, can be large and can produce significant anomaly changes. Therefore, all of the events in

Table I were relocated with depths restrained to our values based on pP, but using the same stations as were used by NOS and reported in the EDR. The number of stations varies between 12 and 126, excluding LONG SHOT. The resulting restrained epicenters are given under the "Adjusted" column in Table I. Also included are columns indicating the estimated reliability of the pP time pick and the shift vectors from the NOS locations to the Adjusted locations. The maximum shift is about 40 km, excluding the nine events appearing in Table Ic. (These nine events are unusual in their signal characteristics and in their anomalies; it is believed that they are multiple events, and they will be analyzed in a special study at a later date.) The reasons for the fact that there are slight differences between the number of stations used by SDL and by NOS are as follows: (1) no stations were included which reported PKP arrival times or two P wave arrivals close together; (2) where two stations are located at virtually the same site (e.g., MBC and NP-NT) only one was used.

Recomputing the anomalies from the Adjusted locations for stations NP-NT and NUR yields the anomaly plots shown in Figures 4a and 4b. A comparison of these results with those in Figures 2a and 2b shows essentially no improvement in the functional patterns. If it is assumed that some of the scatter is due to those events not lying within the Aleutian Islands region proper, these events can be separated and so noted by the circled values in Figures 4a and 4b. A total of 21 events was eliminated in this way; they are listed in Table Ib. However, the anomalies still do not show a consistent enough relation across the region to be used for location purposes.

The question of reading errors being the producer of anomaly errors can be only partly answered. Generally, for the LRSN and VELA stations listed in Table II and the examples in Figures 2 and 4,

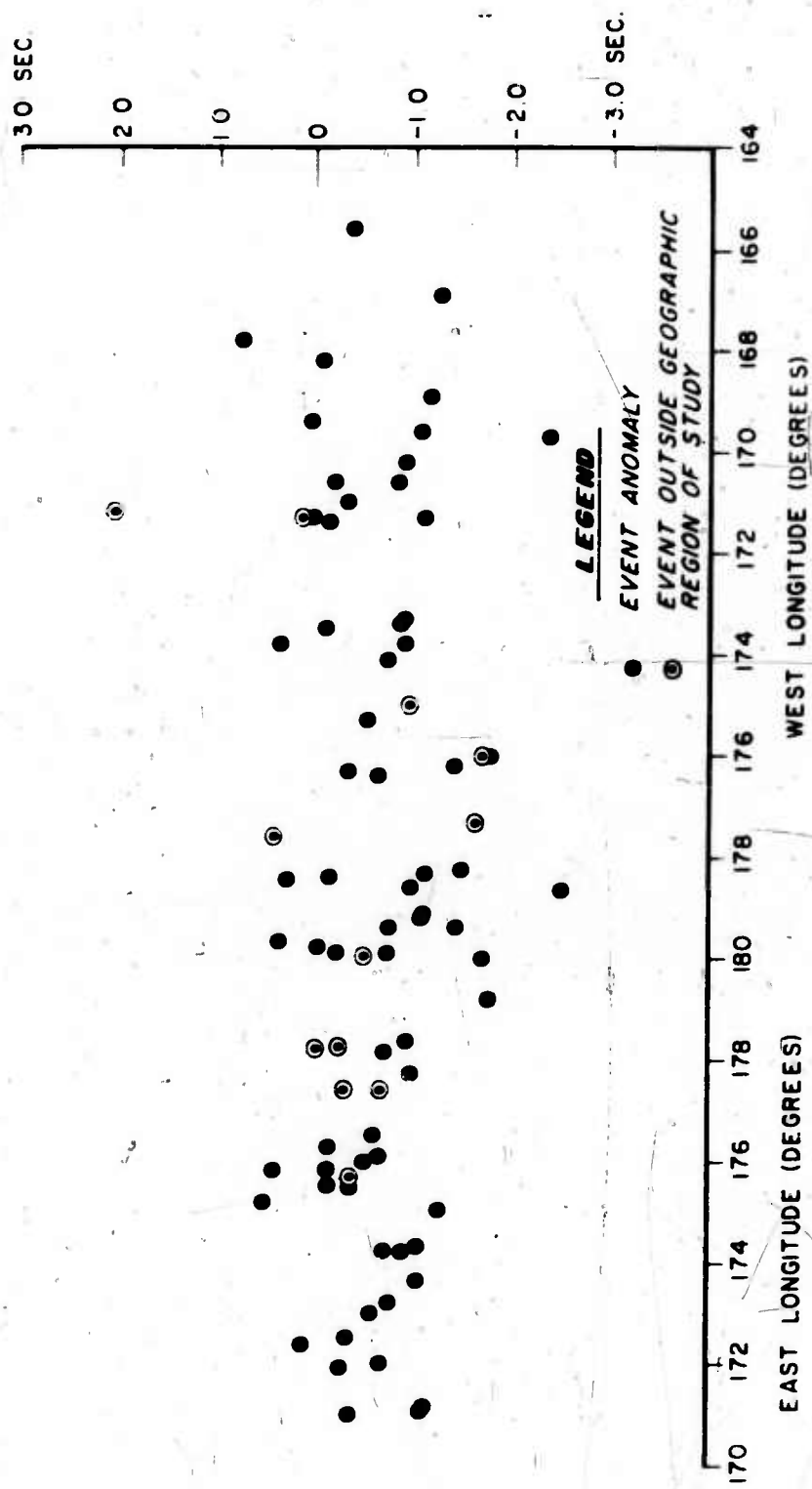


Figure 4b. Anomalies computed from adjusted hypocenters for station NUR.

all arrival times were read by SDL analysts, so reading errors are believed to be acceptably low. Arrival times for other stations were taken from the Earthquake Data Reports published by the NOS. Later in this report we show that these reported times are often in error by as much as one second.

Therefore, the event set in Table I, although largely composed of well-recorded earthquakes, most probably contains location errors of perhaps 30 km, or more and the anomaly inconsistency is not surprising. The possible errors one might encounter when locating events in the Aleutian Islands is demonstrated in the next section.

ERRORS IN LONG SHOT LOCATION USING DIFFERENT STATION NETWORKS

The underground nuclear explosion LONG SHOT was detonated 29 October 1965 on Amchitka Island in the Rat Islands with a yield of 80,000 tons TNT equivalent. P wave signals were well recorded at virtually all distances and azimuths. In their comprehensive report, Lambert et al., (1969) discuss the seismic location made with travel-time data from 329 stations available to them, although probably several hundred more stations recorded the event. The location obtained by restraining the focal depth to the known value and using either the Herrin (1968) or Jeffreys-Bullen tables was approximately 21 km in error to the northwest (Lambert et al., 1969). To now demonstrate the possible variations in location for the Rat Islands region, selected subsets of the 329-station network are taken in different ways and the resultant locations discussed.

First, a network can be defined on the basis of its azimuth aperture or quadrantal coverage. Requiring a minimum aperture of 180° , or two quadrants, and beginning with the sector 0° - 180° (north-east and southeast quadrants), all stations within that azimuth range regardless of distance are used to locate. Increasing the two-quadrant sector by 22.5° , a total of 16 separate locations can be made with networks all having 180° aperture. These results are shown in Figure 5, where the 329-station case is included for comparison, as well as the number of stations for each case, which varies from 57 to 272 stations. The resultant location errors are as small as 13 km and as large as 45 km. There appears to be a preferred shift toward the northwest, suggesting a bias independent of the network although five of the 16 locations shift otherwise.

From the results of this Figure, one can state with some assurance that the epicenters of events in the Rat Islands and

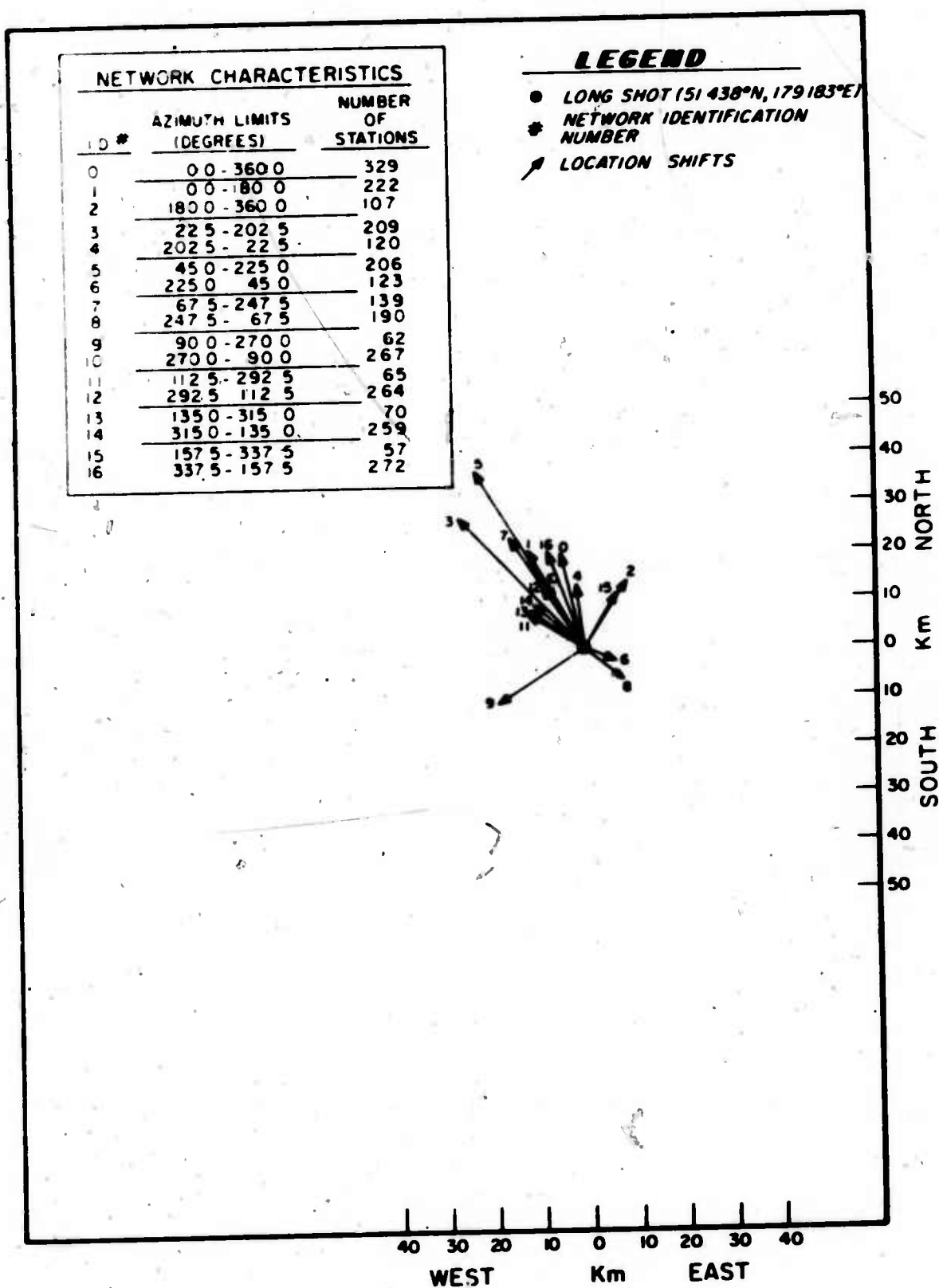


Figure 5. LONG SHOT location errors using two-quadrant networks.

Andreanof Islands (and probably throughout the entire Aleutian Islands) are not known to within 20 km of their true locations, regardless of the distribution or stability of the networks used to locate them. A reiteration of a conclusion previously drawn (Chiburis and Ahner, 1970) is in order: location errors are caused by the set of travel-time anomalies at those stations uniquely defining a particular network; several networks, similarly distributed but composed of different stations, can yield entirely different locations for the same event, even if a randomly selected network sometimes shows a bias due to the source.

If single-quadrant distribution (90° aperture) is accepted as a minimum, instead of two quadrants, and the quadrant is incremented by 22.5° , the resultant locations are shown in Figure 6. The errors now range between 2 km and 163 km, with an average of more than 50 km and no apparent preferred shift direction. The number of stations varies between 22 and 200 with no firm correlation with the size of the error.

If the entire network of 329 stations is now ordered on the basis of increasing azimuth (0° to 360°), and every tenth station of the ordered set is used for locating, a set of nine 32-station networks is obtained, each with approximately four-quadrant coverage. The location results are shown in Figure 7, where a distinct northwesterly error of about 17 km can be observed. This suggests that for the earth model used to compute travel times, those stations that "bear northerly" from LONG SHOT are early in time relative to those stations that "bear southerly". A plot of the zero-mean travel-time anomalies vs azimuth is shown in Figure 8, where the northerly stations, from 340° to 70° azimuth, are indeed seen to be generally early and the southerly stations from 70° to 340° generally late. However, the scatter of the anomalies, even within azimuth windows of 20° - 30° , approaches

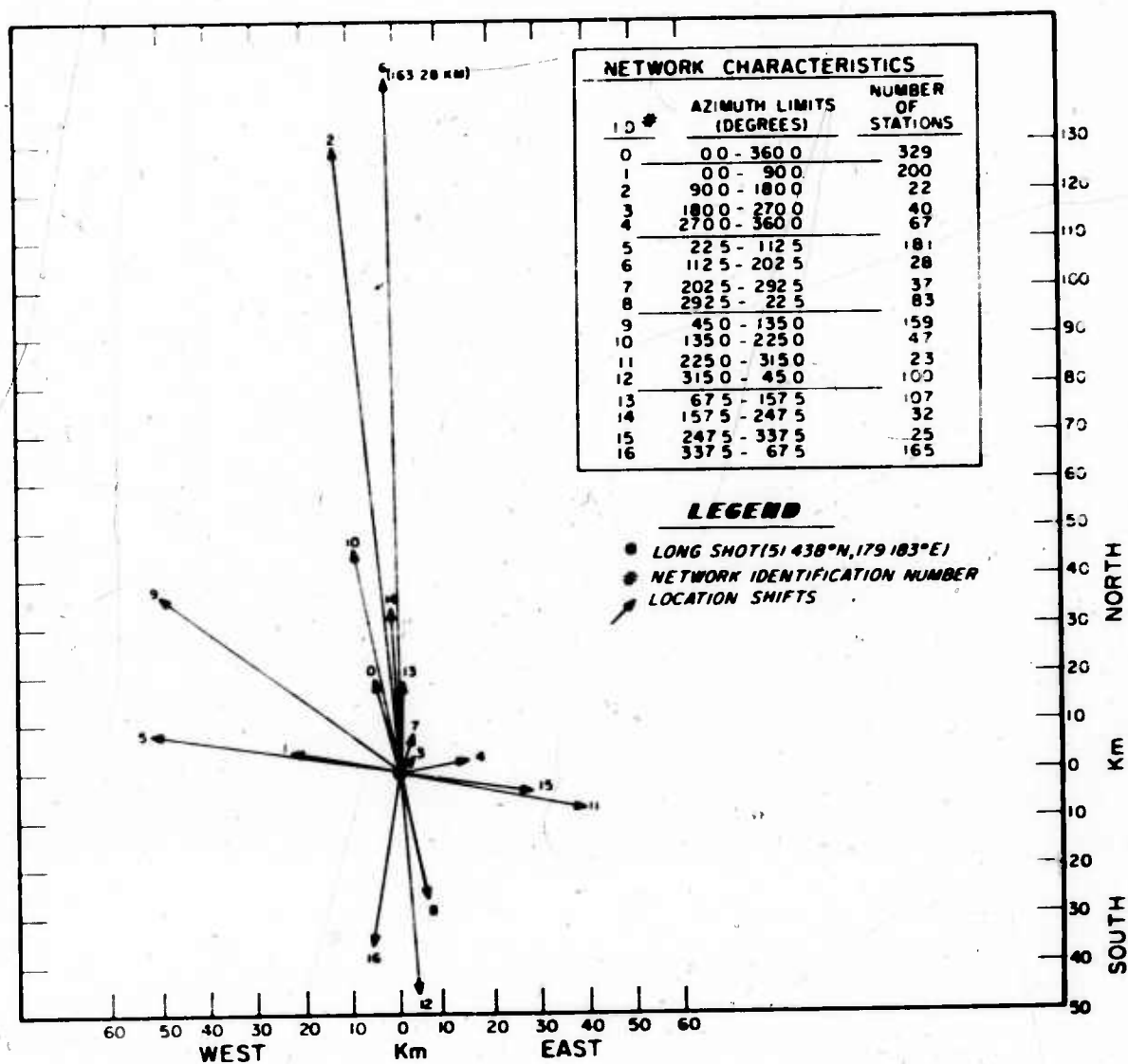


Figure 6. LONG SHOT location errors using single-quadrant networks.

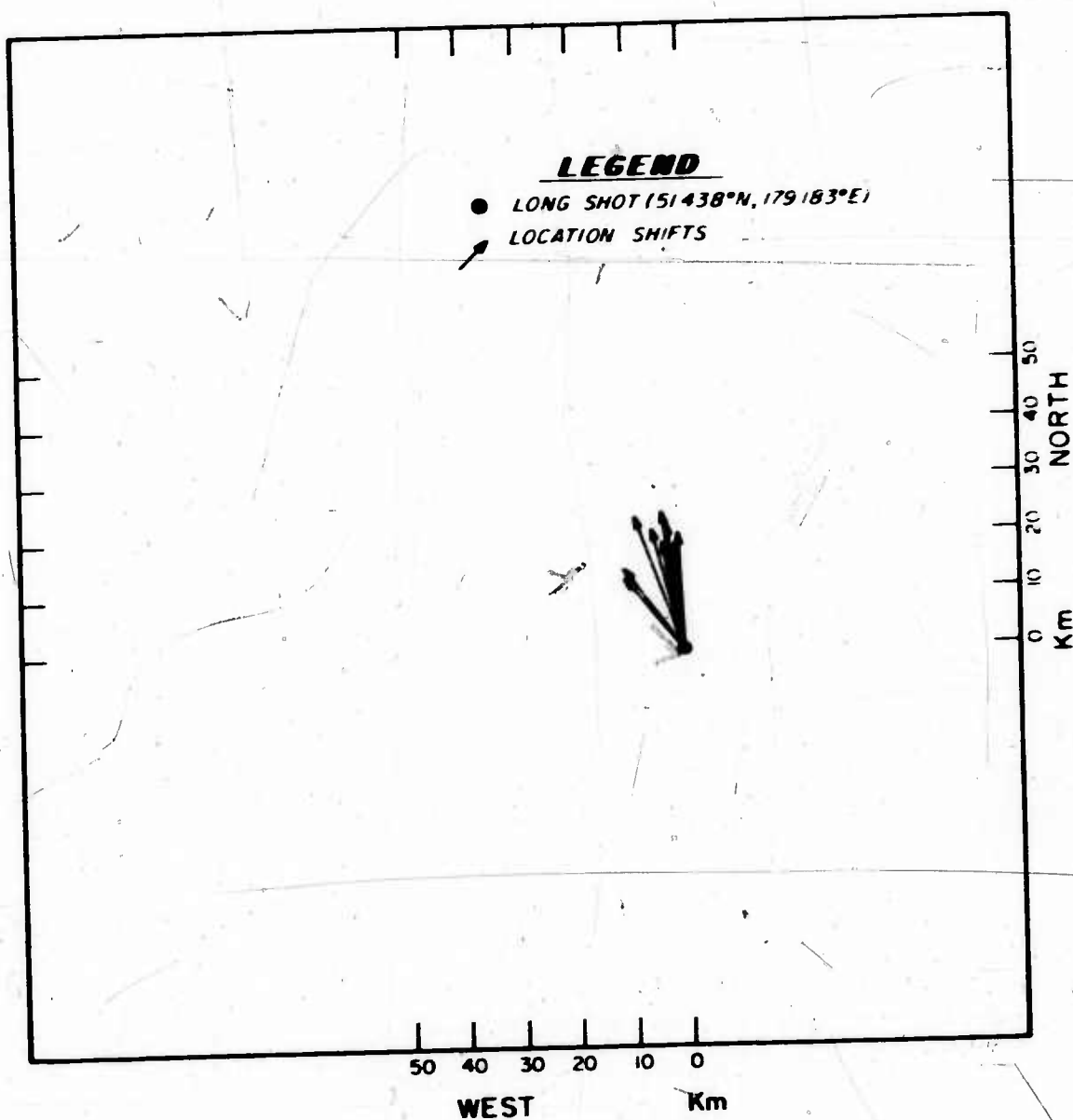


Figure 7. LONG SHOT location errors using four-quadrant, 52-station networks composed of every tenth station selected by increasing azimuth.

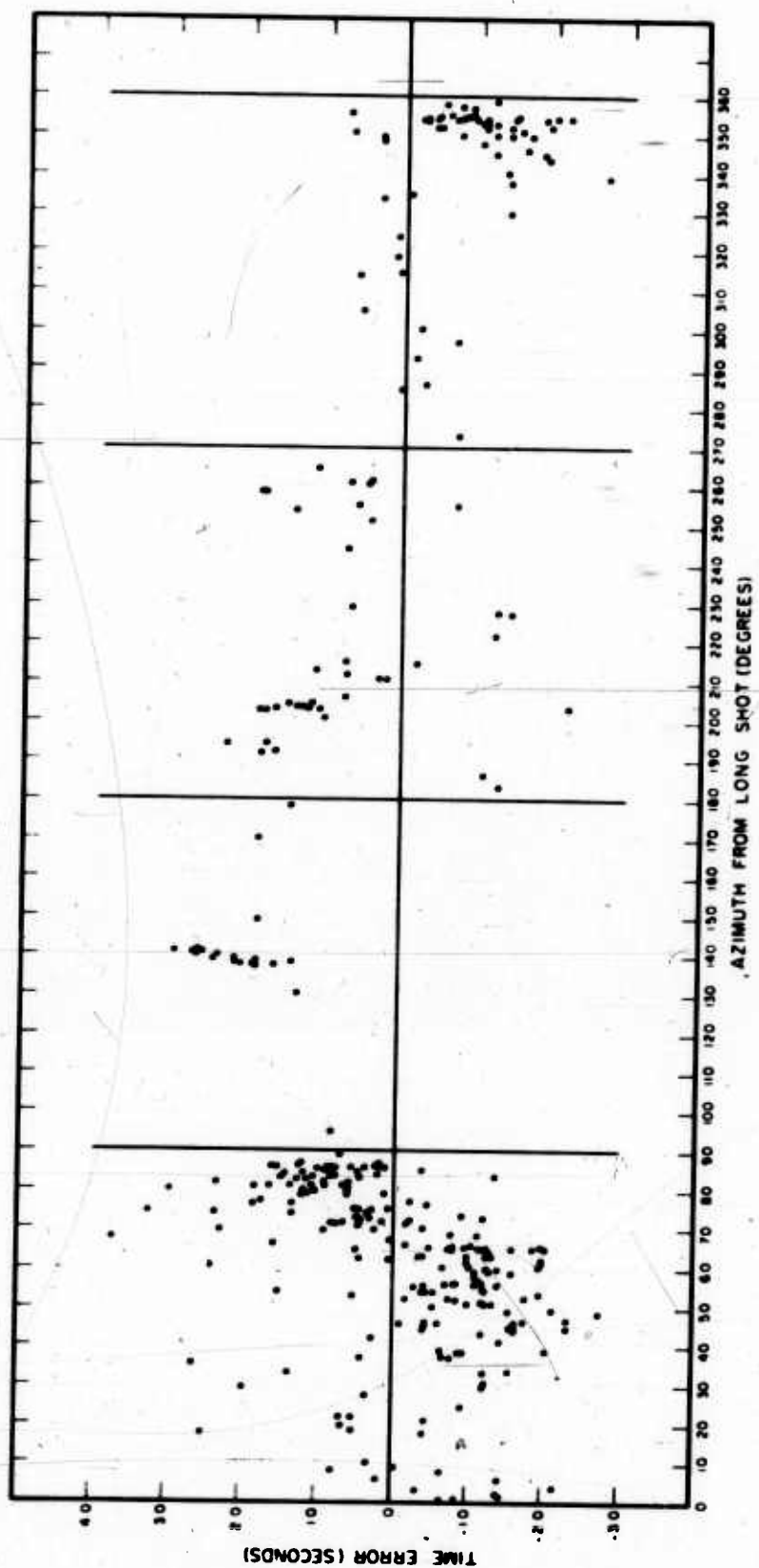


Figure 8. LONG SHOT anomalies as a function of azimuth.

3 sec, which in itself is enough to cause location errors of 50 km. Because of this fact, the practice of fitting a sinusoidal curve through these data in order to predict what the anomalies would be for events occurring in this region is hardly more than an exercise, although it may remove a portion of the bias. For precise location work, anomalies need to be known far better than 0.5 sec; but with a known scatter of 3 sec, any reduction in location errors obtained by applying sinusoidal azimuth-dependent corrections is entirely coincidental. If instead of ordering the station set by azimuth, ordering is on the basis of increasing epicentral distance and every 10th station selected, another set of nine 32-station networks is obtained, again each with approximately four-quadrant coverage. The results are shown in Figure 9, which show about the same northwesterly bias as in the azimuth-ordered results of Figure 7.

In any least-squares procedure of location, the distribution of the true (zero-mean) time errors regardless of distance or azimuth is critical to the result. In order to solve for the correction coefficients, the residual errors are assumed to have the normal distribution about an assumed travel-time distance relationship. But the actual errors for a particular event, may not, and indeed generally do not, have the normal distribution. A plot of the 329 time errors computed from the true location of LONG SHOT is shown in Figure 10a for a 1.0 sec error interval. There is seen to be a definite skewness toward negative errors or early arrival times relative to the earth model; the standard deviation for these data is 1.3 sec. This is another effect of the variation of travel time with azimuth. After least-squares adjusting the epicenter, resulting in a 21 km shift, the minimized zero-mean time errors are shown in Figure 10b. Now the nearly-normal distribution is clear, the standard deviation for these data being 1.0 sec. The assumption made by employing a least-squares scheme in the first place

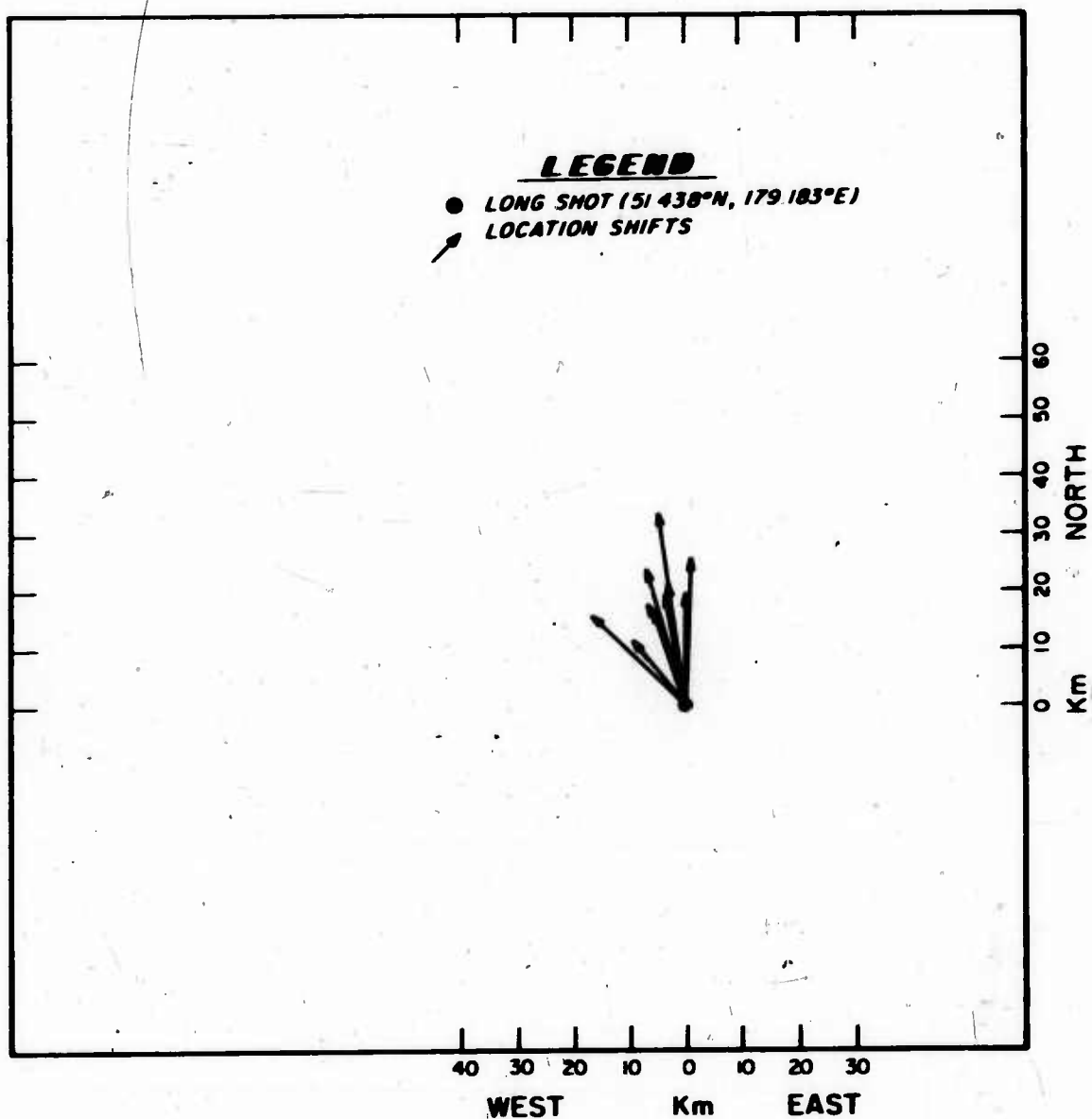


Figure 9. LONG SHOT location errors using four-quadrant, 32-station networks composed of every tenth station selected by increasing distance.

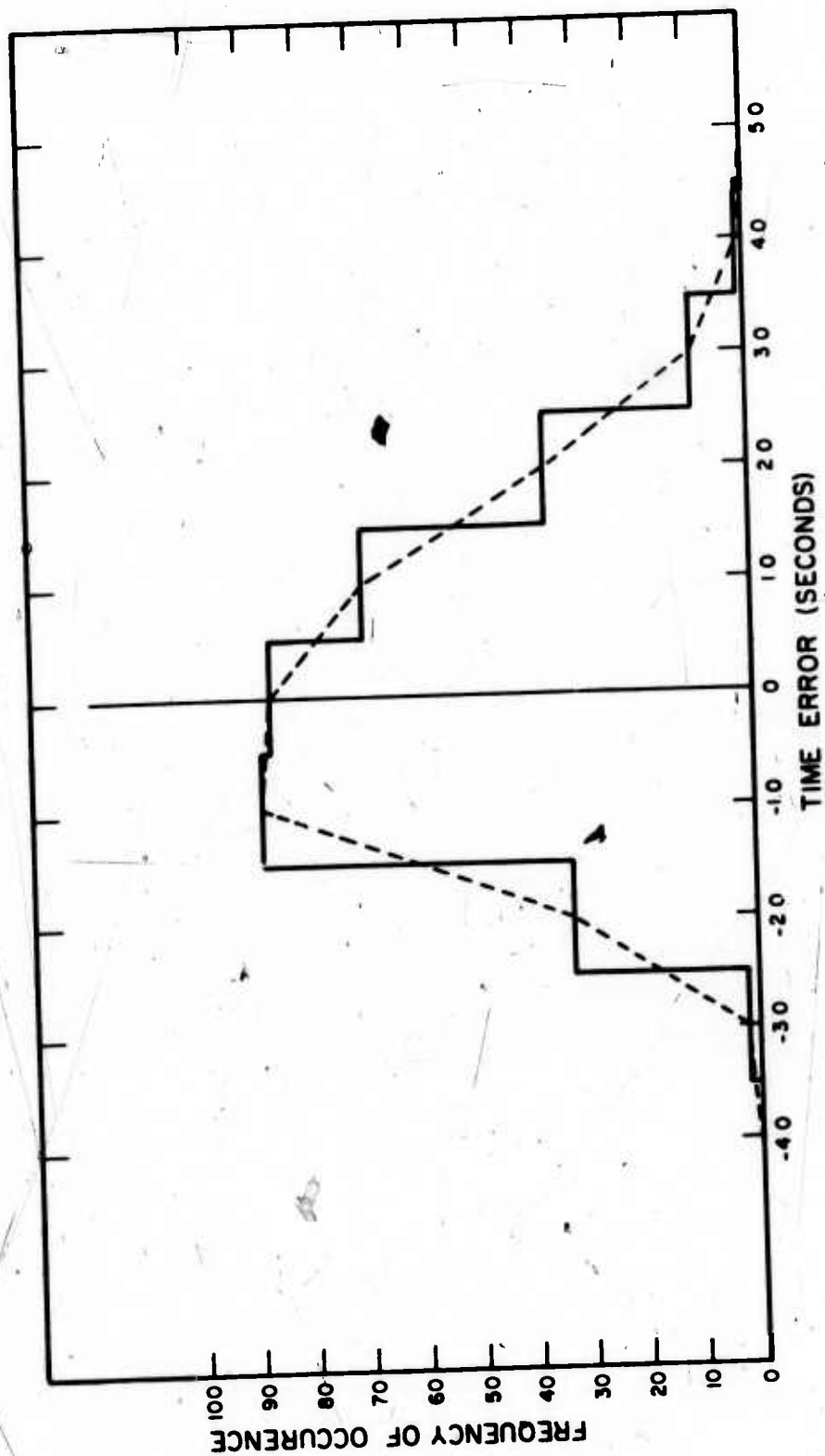


Figure 10a. LONG SHOT zero-mean error distribution computed from known location.

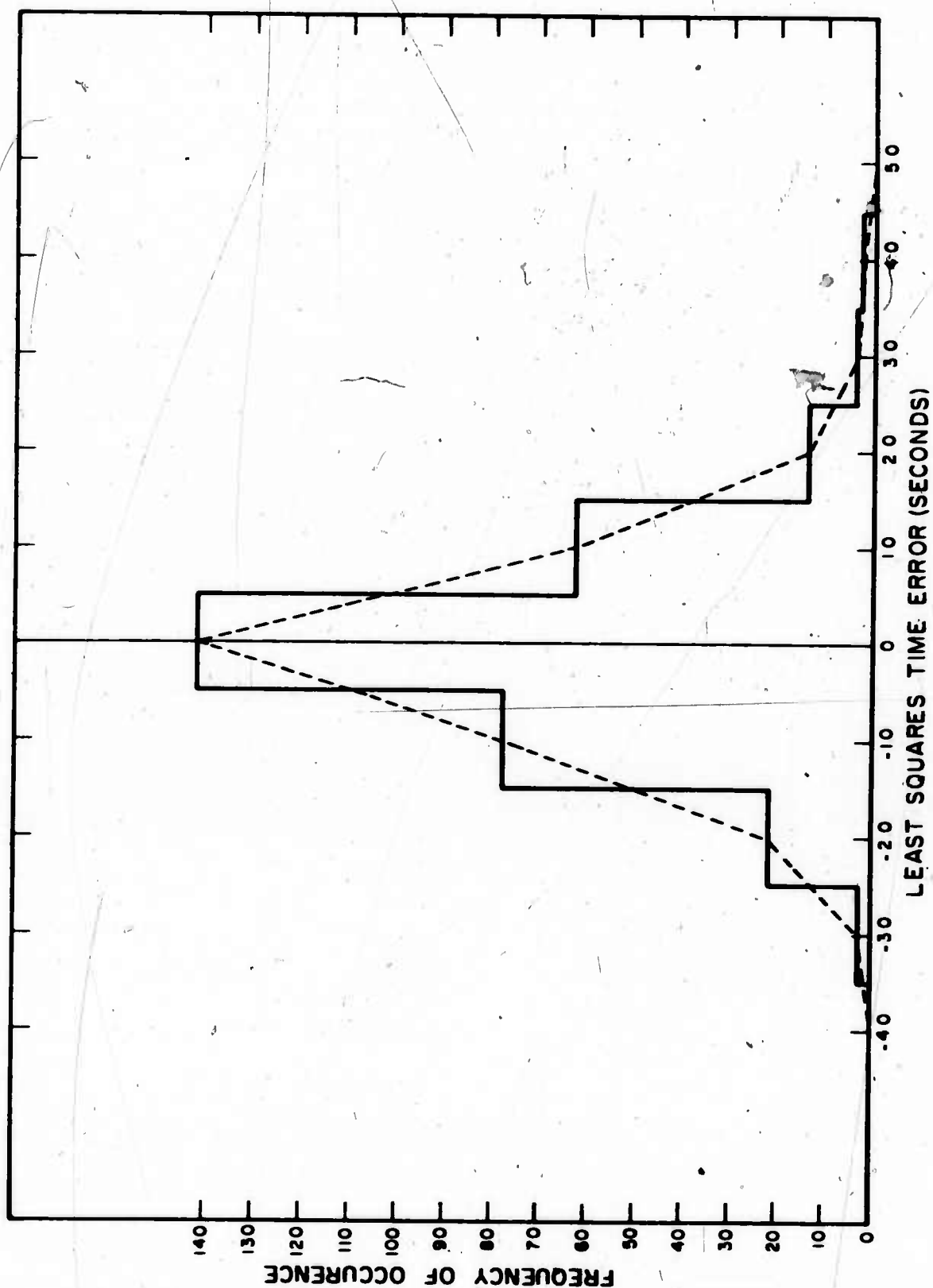


Figure 10b. LONG SHOT zero-mean least-squares error distribution computed from 329-station solution.

is that any subset of travel-time anomalies, even a large one (Figure 10a), has a normal distribution and must be minimized because of random imperfections not because of systematic early or late arrival times. The anomalies are due to lateral and vertical inhomogeneities which are not allowed for in the earth model; the actual effects of these inhomogeneities may be large and nothing dictates that a particular set of anomalies for the network locating the event should be as small as possible in a least-squares sense. The only errors which should ever be minimized are those due to reading precision; these are random and probably have a zero-mean normal distribution.

From the above results, an example can be given of the difficulty in working with a mislocated earthquake data set and of possible anomaly errors computed from the various LONG SHOT solutions for station NP-NT. The anomaly inconsistency for this station is shown in Table III, in which the range is 11.44 sec. If LONG SHOT had been an earthquake, any one of these epicenters might have been reported, depending on the particular network available at the time of occurrence, and hence, any one of these anomalies would have been computed and accepted. But if accurate locations are to be realized for a particular region, anomalies must be known to within 0.25 sec, including reading error; an 11 sec uncertainty is useless.

The principal conclusion to be drawn from the preceding exercise is that by studying anomalies across a region as large as the Aleutian Islands (approximately 1600 km in extent) and that by using earthquakes which are all differently mislocated, the anomalies must be expected to display variations and inconsistencies which are not real. However, even if event mislocation is the chief cause of the variations, an attempt can be made to achieve both anomaly and location consistency, no matter how

TABLE III
TRAVEL-TIME ANOMALIES AT NP-NT COMPUTED FROM VARIOUS LONG SHOT SEISMIC SOLUTIONS.

Long Shot Location	Method of Selecting the Network	Number of Stations	Azimuth Range (In Degrees)	Actual Aperture (In Degrees)	Distance Range (In Degrees)	NP-NT Anomaly Relative to UMD10 (In Seconds)
1	All Stations	329	0-360	359	20-99	+0.02
2	180° Sector	222	0-180	176	20-99	+1.28
3	180° Sector	107	180-0	177	32-98	+1.53
4	180° Sector	209	22.5-202.5	176	20-99	+0.48
5	180° Sector	120	202.5-22.5	179	20-98	+2.42
6	180° Sector	206	45-225	177	22-99	+0.79
7	180° Sector	123	225-45	178	20-96	+2.79
8	180° Sector	139	67.5-247.5	177	33-98	-0.34
9	180° Sector	190	247.5-67.5	177	20-99	+1.85
10	180° Sector	62	90-270	152	31-98	-0.59
11	180° Sector	267	270-90	163	20-99	+0.06
12	180° Sector	65	112.5-292.5	149	32-96	+0.99
13	180° Sector	264	292.5-112.5	154	20-99	+0.83
14	180° Sector	70	135-315	176	32-98	+0.97
15	180° Sector	259	315-135	132	20-99	+0.89
16	180° Sector	57	157.5-337.5	175	32-98	+0.93
17	180° Sector	272	337.5-157.5	171	20-99	-0.38
18	90° Sector	200	0-90	86	20-99	-1.42
19	90° Sector	22	90-180	38	36-76	-1.12
20	90° Sector	40	180-270	87	32-98	-7.50
21	90° Sector	67	270-360	75	57-91	+0.09
22	90° Sector	181	22.5-112.5	63	20-99	-0.39
23	90° Sector	28	112.5-202.5	62	36-97	+2.42
24	90° Sector	37	202.5-292.5	65	32-98	+0.89
25	90° Sector	83	292.5-22.5	49	20-96	+0.39
26	90° Sector	159	45-135	42	22-99	-1.57
27	90° Sector	47	135-225	84	35-98	+3.76
28	90° Sector	23	225-315	87	32-96	+2.84
29	90° Sector	100	315-45	90	21-96	-1.79
30	90° Sector	127	67.5-157.5	81	33-98	-2.55
31	90° Sector	32	157.5-247.5	84	47-98	+1.14
32	90° Sector	25	247.5-337.5	83	32-91	+1.86
33	90° Sector	165	337.5-67.5	89	20-99	-1.25
34	Every Tenth Station: By Azimuth	32	0-360	354	22-99	-1.64
35		32	0-360	354	22-89	+1.26
36		32	0-360	353	22-93	+1.07
37		32	0-360	352	20-95	+1.42
38		32	0-360	352	21-93	+1.36
39		32	0-360	351	20-96	+1.14
40		32	0-360	349	33-96	+1.19
41		32	0-360	349	22-96	+1.47
42		32	0-360	347	33-92	+1.66
43		32	0-360	347	23-98	+1.89
44	By Distance	32	0-360	337	20-90	+1.19
45		32	0-360	339	20-98	+1.06
46		32	0-360	353	21-91	+1.19
47		32	0-360	352	22-91	+1.22
48		32	0-360	321	22-91	+1.00
49		32	0-360	316	22-92	+1.40
50		32	0-360	350	22-92	+1.98
51		32	0-360	354	22-92	-1.55
52		32	0-360	348	22-92	+1.09
53		32	0-360	345	23-93	+1.12
MAXIMUM ANOMALY						+8.89
MINIMUM ANOMALY						-2.55
ANOMALY RANGE						11.44

artificial the anomaly functions and the relative locations appear to be. With the LONG SHOT explosion providing a "bias" constraint in the vicinity of Amchitka Island, relative locations can be made using functional anomalies at increasing distances from LONG SHOT, always demanding least-squares consistency and reasonable functions..

DETERMINATION OF ANOMALY FUNCTIONS

Selection of a constant network

It was shown in a previous report (Chiburis and Ahner, 1970), as well as in the preceding section, that "location bias" is a function of the particular network used; also, if a constant network is used for locating a set of events in one region, relative accuracy within the event set is not affected, although all of the events may be translated by an unknown bias. However, if different networks are used to locate different events, the results of locating in a particular region display large unpredictable errors, unless anomalies are applied.

Therefore, in this report, in order to remove the network effect, a constant network is selected, all stations of which recorded a suitable number of the events in Table I. Subsets of this network can then be used to demonstrate location consistency.

Initially, the constant network was composed of seven LRSM and VELA stations and eight NOS and participating stations. The number of events was ten. Various techniques were initially employed to achieve consistency, none of which yielded satisfactory results. Eventually it was suspected that the reported arrival times at NOS stations were partly responsible for the poor results. An effort was made to obtain the seismograms from the NOS library in order to check the readings. Only those seismograms from the WWSS system were available; the seismograms from participating stations were not. Table IV is a list of only those reading discrepancies greater than 1.0 sec found at eleven selected WWSS stations for a set of 50 events.

A total of 279 readings was compared. Of these, 40 were different by more than 1.0 sec and 114 by more than 0.5 sec. Consequently,

TABLE IV

Selected Arrival-Time Discrepancies Greater than 1.0 Sec
(SDL - NOS)

-1.4	+1.8	-1.7	-1.1	-2.0	-1.0	-2.0	+1.4
+1.0	+1.4	+1.4	-1.5	-1.9	+1.7	+2.1	+1.4
+2.1	+1.0	-1.0	-1.2	-1.0	-1.0	-1.5	-1.8
-1.4	-1.7	-2.4	-1.1	-1.0	+1.1	-2.1	-1.7
-1.0	+1.0*	-1.0*	-1.1	-1.3	-19.9*	+1.2	-1.3

*Reading not used by NOS in location reported.

all readings used in the rest of this report are only those for which seismograms were obtained and analyzed at SDL.

The constant network finally selected, referred to as Network 1, is composed of fourteen stations. Three subsets of this network were devised (Table V). Also given in this table are seventeen events, each of which was recorded by all fourteen stations. The LONG SHOT explosion is included in this set, but not FLEXBAG, because it was not recorded by all fourteen stations. Therefore, only one event serves as bias control for the study. A geographic map of the seventeen events is shown in Figure 11. Although farther apart than desired, the number of events is the maximum obtainable for as many as fourteen stations. By decreasing the number of stations, one could obtain more events, but the network would be less effective in azimuth and distance distribution.

Initial locations

Using the Adjusted locations given in Table I as the input parameters, the seventeen events were located by the four networks with raw arrival times. Recall that the Adjusted locations are relocations of NOS hypocenters with depths restrained to pP readings. The shifts from the input location are shown in Figure 12 on a magnified scale. The four networks yield locations which disagree with the input location by over 60 km for some events, and the scatter within the clusters is as large as 35 km. The reason for this poor result is that the networks are composed of different sets of stations which have quite different distributions of anomalies. The clustering and standard deviations of the least-squares solutions for the seventeen events are listed in Table VI. Several standard deviations become quite small, showing that small residuals are a necessary but not sufficient indication of accuracy.

TABLE V

Network #1	Network #2	Network #3	Network #4	Altitude from Long Shot (in Degrees)	Distance from Long Shot (in Degrees)	Number from Table 1	Date	Designation
ND1	ND1			297	75	1	01 Jun 67	Fox 1
Q01	Q01			305	79	3	19 Jun 67	Fox 2
						6	06 Jul 67	Fox 3
N0R	N0R			317	66	18	23 Jan 68	Fox 1
						22	15 Feb 68	Fox 5
						23	19 Jul 66	AND 6
S10	S10			353	80	25	22 Jul 66	AND 7
						31	21 Feb 68	AND 8
N0R	N0R			003	47	47	15 May 66	AND 9
NP-N1	NP-N1			022	34	48	11 Jun 66	AND 10
						58	27 Nov 65	AND 11
						63	29 Oct 65	Rat 12 (Long Shot)
CO1	CO1			039	22	84	04 Jul 66	Rat 13
						86	27 May 67	Rat 14
IN-N1	IN-N1			044	67	107	26 Feb 66	Neat 15
						106	13 Jan 66	Neat 16
RA-ON	RA-ON			054	51	108	08 Jan 66	Neat 17
LA010	LA010			065	47			
WP006	WP006			072	59			
OP010	OP010			074	49			
FF060	FF060			081	52			
				082	53			
Total Stations	14		8					
Portfire	11	10	10					

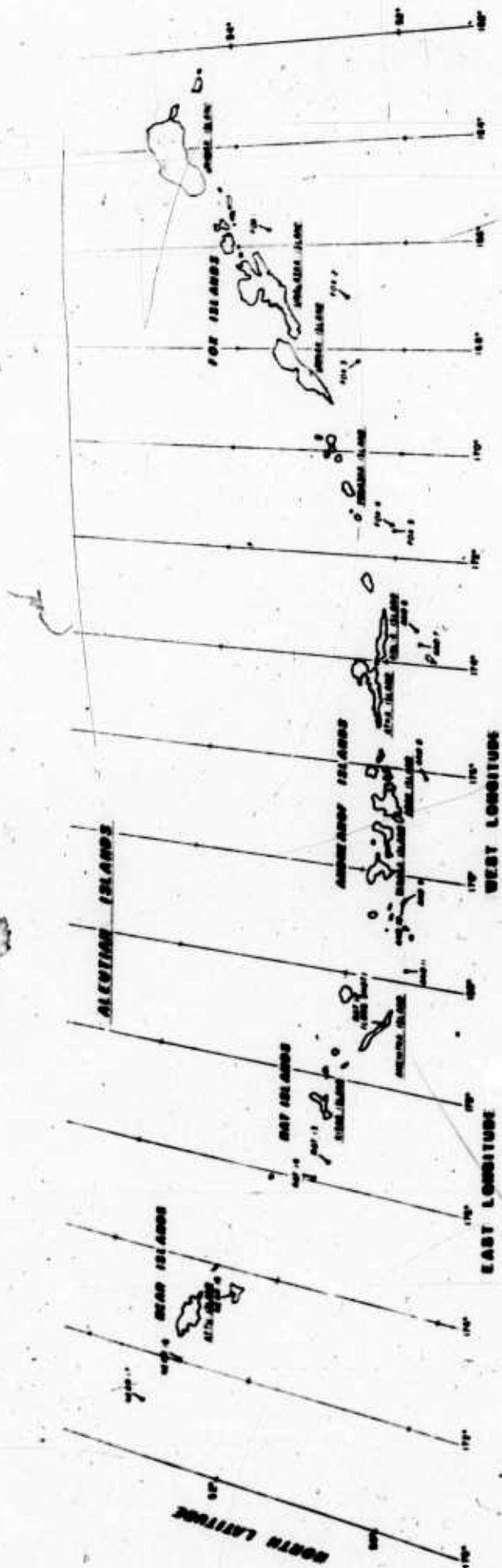


Figure 11. Geographic location map of 17 selected events.

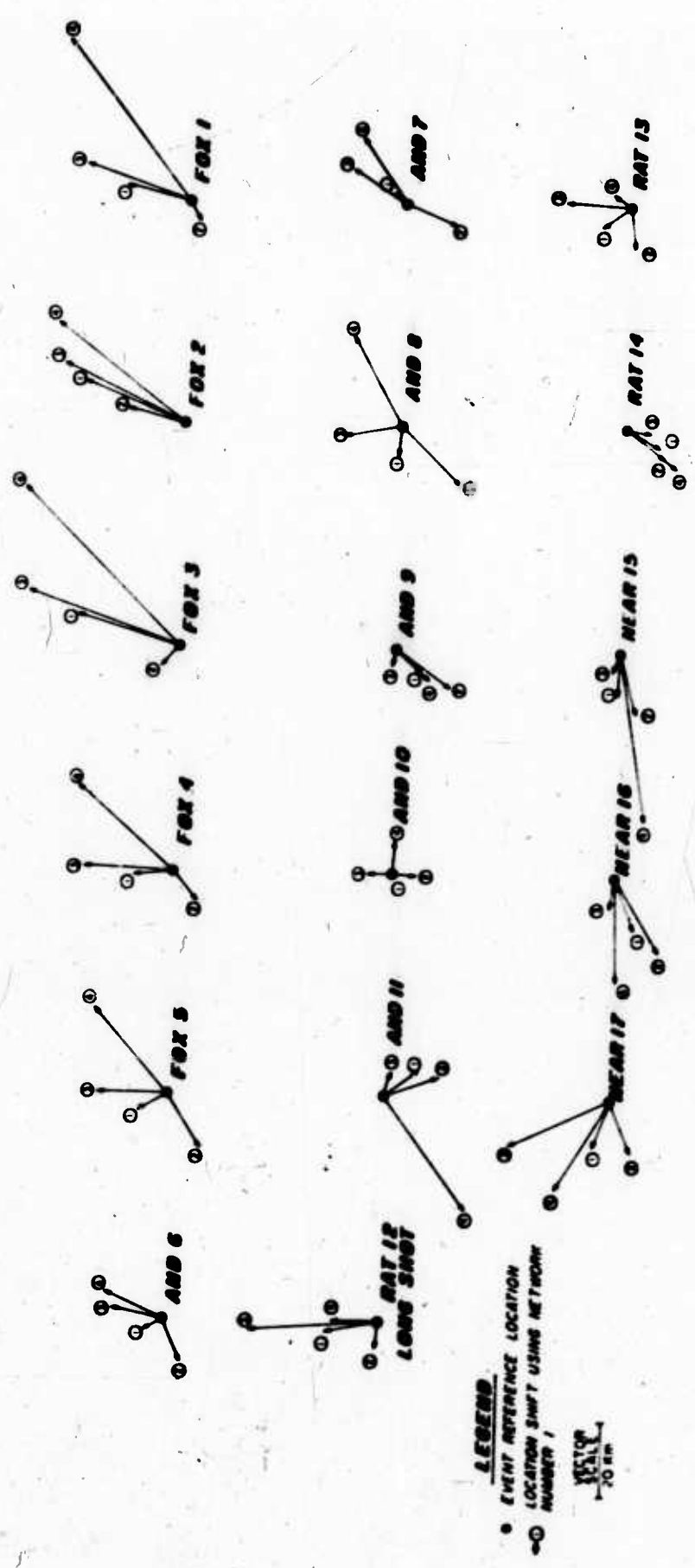


Figure 12. Location shifts for four networks obtained without anomaly corrections.

TABLE VI
LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED WITHOUT
ANOMALY CORRECTIONS

	Box 1				Box 2				Box 3				Box 4				Box 5				Box 6				Box 7				Box 8				Box 9				
	Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts		Location Shifts								
	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to	from	to							
	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)						
1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0							
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0							
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0							
Mean	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0							

LONG SHOT anomalies for corrections

The LONG SHOT anomalies, which are accurately known, are given in Table VII for the fourteen stations. If it is assumed that these anomalies are valid across the entire Aleutian region, they can be applied as corrections to all arrival times. The location results of doing this are shown in Figure 13. Several of the events, particularly in the Fox Islands, now tend to approach a tighter cluster of solutions for the four networks. But for the Andreanof 9, 10, 11, and the Rat Near events, no improved clustering is observed. In fact, when no anomalies were applied, far greater clustering was obtained for these events (Figure 12); regardless of the clustering, the standard deviations are generally now larger (Table VIII). This implies that a poorer travel-time fit is being obtained in the least-squares scheme when LONG SHOT anomalies are used as corrections.

Both network clustering and a reduction in the standard deviation (or an approach to an acceptable value -- say 0.25 - 0.50 sec) are necessary in order to achieve consistency and relative accuracy; but they are not, alone or together, sufficient to obtain absolute accuracy (complete removal of "bias"). The only known way to achieve absolute accuracy is to have seismic data available from a known explosion previously detonated in the vicinity. One might expect that LONG SHOT would approximately calibrate adjacent regions. In fact toward the east the standard deviations decrease for Andreanof -11, -10, and -9 when using the LONG SHOT anomalies. However, the clustering results for these same events are worse; thus the results are inconclusive.

As the LONG SHOT anomalies are not valid except in the immediate vicinity of Amchitka Island, and possibly eastward for

TABLE VII
LONG SHOT Anomalies for 14 Stations Relative to UBO

<u>Station</u>	<u>Observed Long Shot Anomalies in Seconds</u>
NDI	-1.23
QUE	-0.10
NUR	-1.46
STU	-2.74
NOR	-0.72
NP-NT	0.02
COL	-1.39
HN-ME	-2.21
RK-ON	-2.12
LA010	-1.29
WM006	-0.54
UB010	0.00
TF060	0.62
TUC	0.10

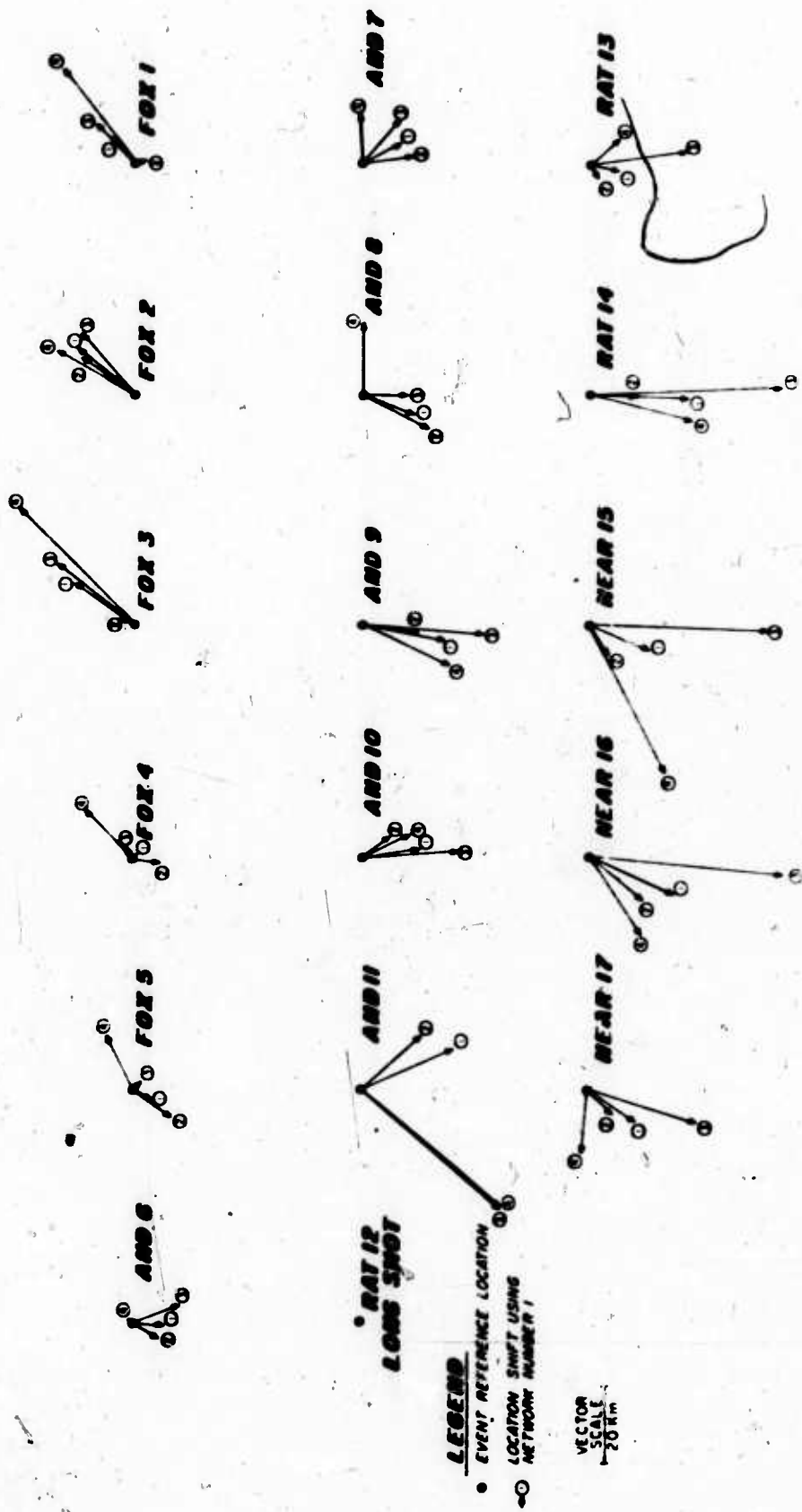


Figure 13. Location shifts for four networks obtained by applying LONG SHOT anomalies.

TABLE VIII
LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY
APPLYING LONG SHOT ANALOGIES

Network	For 1			For 2			For 3			For 4			For 5			And 6			And 7			And 8			And 9		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)
1	8.5	1.118	4.0	10.8	1.014	4.4	1.7	.884	4.4	1.7	.884	4.4	1.7	.884	4.4	1.7	.884	4.4	1.7	.884	4.4	1.7	.884	4.4	1.7	.884	4.4
2	11.9	1.195	15.2	11.9	1.315	19.6	1.3	1.113	11.3	1.3	1.113	11.3	1.3	1.113	11.3	1.3	1.113	11.3	1.3	1.113	11.3	1.3	1.113	11.3	1.3	1.113	11.3
3	14.6	1.556	11.2	27.4	1.315	3.7	4.5	1.015	0.8	12.7	1.636	12.0	7.3	.732	4.8	14.0	.696	8.0	19.6	.633	12.0	15.7	.825	6.8	22.2	.514	2.0
4	11.0	.925	18.4	24.9	.926	4.8	18.8	.803	16.0	15.0	.728	16.8	1.3	.974	8.0	12.5	1.018	10.8	18.7	.709	22.0	25.1	.487	6.0	25.1	.487	6.0
Mean	14.4	.998	10.7	21.3	1.039	5.5	21.1	.919	11.8	7.0	.801	7.9	9.7	.808	8.6	7.2	.928	5.6	16.7	.776	10.8	23.9	.435	6.4	23.9	.435	6.4

Network	And 10			And 11			Net 12			Net 13			Net 14			Near 15			Near 16			Near 17			Average of Shifts from Mean		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)	From Input (km)	From Mean (km)	σ (km)
1	15.8	.865	1.8	26.8	.473	10.4	00	00	00	7.9	.767	4.0	25.0	.747	3.8	17.6	.911	9.6	25.1	1.103	3.2	15.3	.911	2.4	15.3	.911	2.4
2	10.5	.364	8.0	21.1	.175	18.4	00	00	00	4.5	.746	10.7	13.0	.575	18.8	9.6	.802	18.1	18.7	.912	10.8	9.9	.753	6.0	9.9	.753	6.0
3	20.1	.720	10.4	19.4	.186	11.6	00	00	00	25.5	1.513	15.1	11.0	.600	22.4	4.6	.558	24.0	52.1	1.039	27.2	29.9	.853	15.0	29.9	.853	15.0
4	15.0	.421	5.6	38.6	.396	13.6	00	00	00	10.0	.644	6.8	28.4	.576	5.6	19.6	.710	25.6	25.6	.770	14.3	16.6	.653	11.5	16.6	.653	11.5
Mean	16.8	.510	5.9	34.0	.392	24.0	00	00	00	12.0	.673	9.1	29.1	.640	12.1	19.6	.745	20.4	30.1	.976	21.9	17.9	.731	10.7	17.9	.731	10.7

a short distance, a set of anomaly functions, one for each station, needs to be derived which will provide consistency, network clustering, and acceptable standard deviations across the entire Aleutian Islands. It would be trivial to draw functions exactly through the anomalies in Figures 4a and 4b, which are simply the anomalies from the Adjusted locations, for two reasons: first, it is hoped that the anomalies would not change as drastically as shown over such small distances, and second, that there should be at least a suggestion of the anomaly being monotonic or having a smooth rate of change over distances of 500 km or so. In other words, the functions that one derives should be geophysically realistic.

Simple functional anomalies

If it is assumed that the anomaly variations produced by the earth are greater than the errors due to mislocation or to measurement, the Adjusted locations can be used to compute anomalies at all of the stations and to estimate anomaly functions by fitting a linear relation through the anomalies for each station. Because the LONG SHOT anomalies are accurately known, bias constraints are available for each of the curves on the anomaly axes. These curves and their translations are shown in Figures 14a and 14b.

A linear function is the simplest possible and provides a starting point from which more complex functions can be devised.

If these values are now applied as a function of longitude, the event set can be located by the four networks, the results of which are plotted in Figure 15 and listed in Table IX. Except for Andreanof-11, it can be seen that both clustering and reduction in standard deviation are being accomplished about the same as in Figure 13. The four network solutions for an event are now

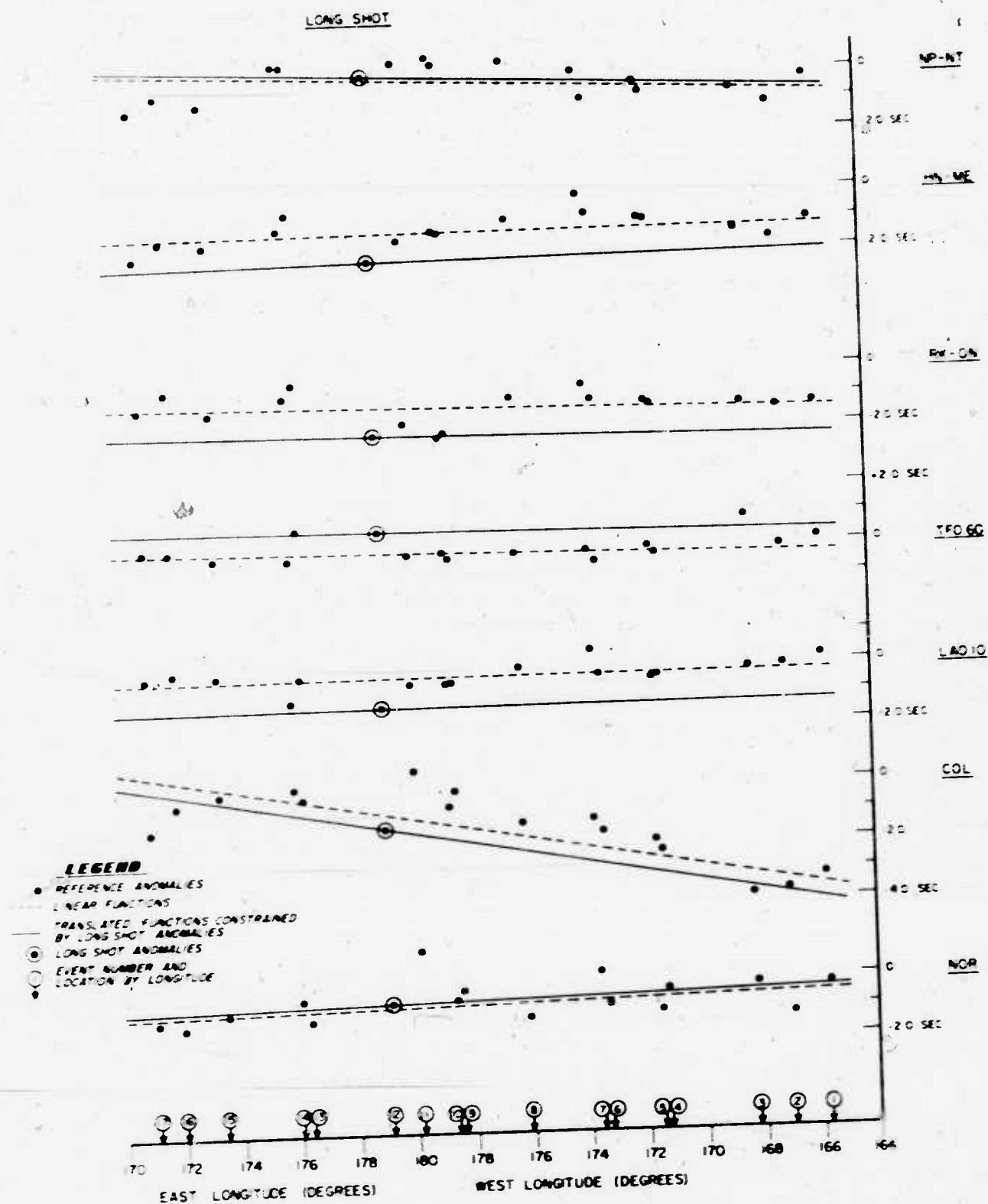


Figure 14a. Determination of simple functional anomalies.

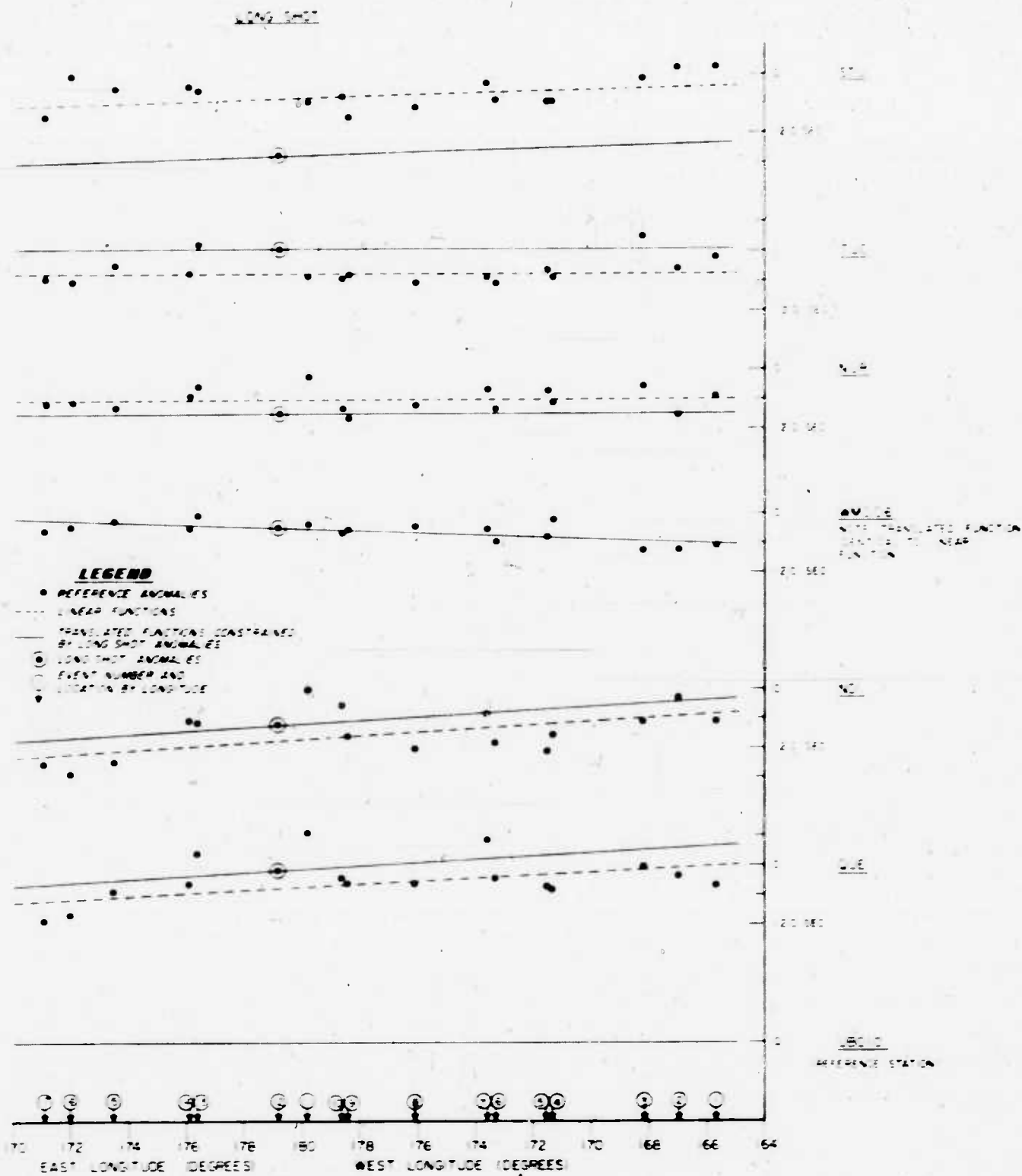


Figure 14b. Determination of simple functional anomalies.

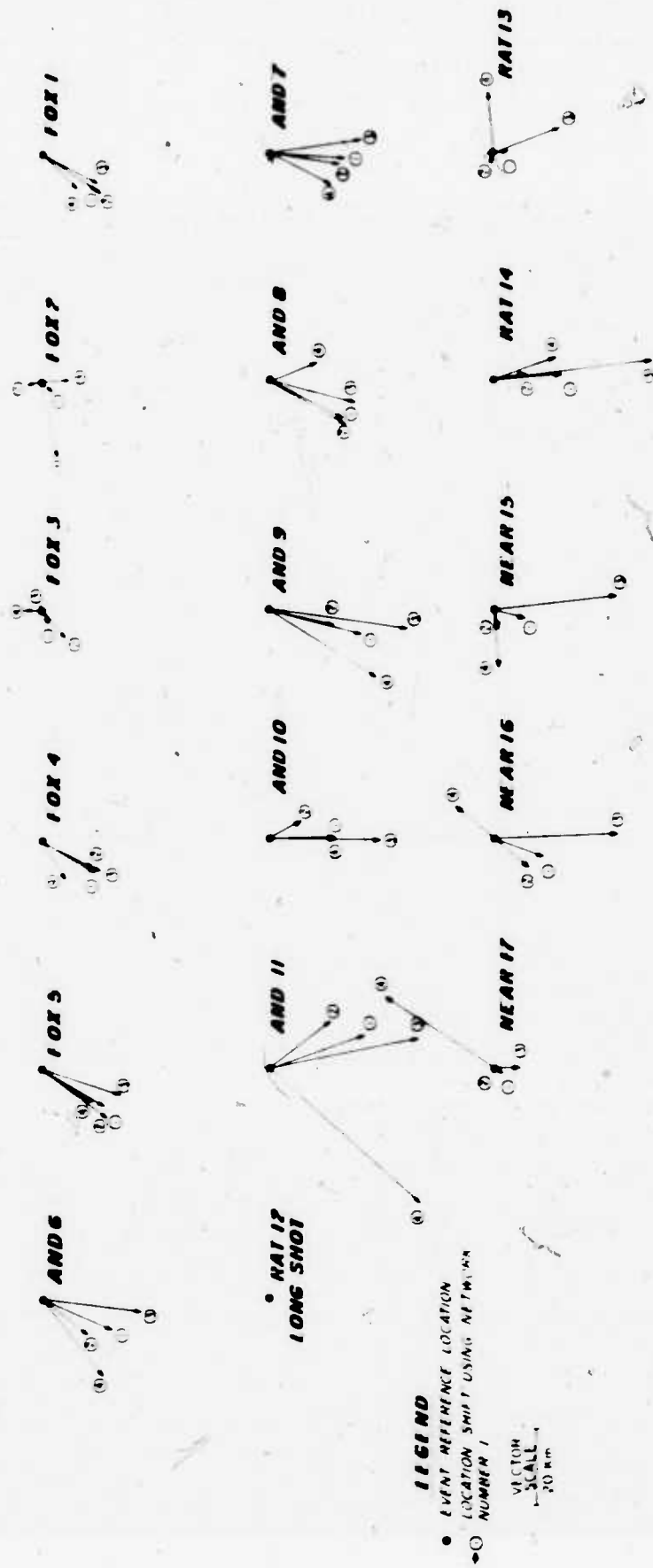


Figure 15. Location shifts for four networks obtained by applying simple functional anomalies.

clustered within approximately 9 km of the mean location, although the mean locations are as far as 20-30 km from the input epicenter. The standard deviations are generally improved, but not to low enough values. If the Near Islands events are excluded, the clustering error would reduce to about 6.6 km. The average clustering error of the Near events is more than 14 km. This poor result is expected, because the anomalies for these events show the largest departure from the linear functions in Figures 14a and 14b.

Summarizing the clustering and standard deviations for the cases considered thus far, the shifts from the input location are as large as 33 km, but the parameter of importance is the average shift from the mean location obtained using the four networks. When no anomalies are applied (Table VI), the shifts from the mean do not improve much over the shifts from the input location, the average being about 15 km but with some as large as 31 km. Therefore, no significant improvement in clustering is obtained without anomalies. The standard deviations are still too large (up to 1.0 sec) to claim consistency.

For the LONG SHOT anomaly case (Table VIII), a small improvement in clustering is obtained through the Fox Islands and into the Andreanof Islands, but not for Andreanof -8, -11, Rat -14, nor any of the Near Islands events. However, the standard deviations (up to 1.5 sec) are now larger for every event and each network, except Andreanof -9, -10, and -11. This may suggest that the LONG SHOT anomalies are approximately valid toward the east from Amchitka Island, but not at all toward the west.

The location results of applying simple linear functional anomalies (Table IX) are that the clustering in the Fox Islands and part-way into the Andreanof Islands is very good, but for Andreanof-11 and for the Rat and Near Islands, the clustering fails.

TABLE 1
LOCATION INPUTS, LOCATION LOCATIONS, AND CUMULATIVE TOTALS FOR 1940-1949

No. of birds	Loc. 1		Loc. 2		Loc. 3		Loc. 4		Loc. 5		Loc. 6		Loc. 7		Loc. 8		Loc. 9		Loc. 10		Loc. 11		Loc. 12		Loc. 13		Loc. 14		Loc. 15		Loc. 16		Loc. 17		Loc. 18		Loc. 19		Loc. 20		Loc. 21		Loc. 22		Loc. 23		Loc. 24		Loc. 25		Loc. 26		Loc. 27		Loc. 28		Loc. 29		Loc. 30		Loc. 31		Loc. 32		Loc. 33		Loc. 34		Loc. 35		Loc. 36		Loc. 37		Loc. 38		Loc. 39		Loc. 40		Loc. 41		Loc. 42		Loc. 43		Loc. 44		Loc. 45		Loc. 46		Loc. 47		Loc. 48		Loc. 49		Loc. 50		Loc. 51		Loc. 52		Loc. 53		Loc. 54		Loc. 55		Loc. 56		Loc. 57		Loc. 58		Loc. 59		Loc. 60		Loc. 61		Loc. 62		Loc. 63		Loc. 64		Loc. 65		Loc. 66		Loc. 67		Loc. 68		Loc. 69		Loc. 70		Loc. 71		Loc. 72		Loc. 73		Loc. 74		Loc. 75		Loc. 76		Loc. 77		Loc. 78		Loc. 79		Loc. 80		Loc. 81		Loc. 82		Loc. 83		Loc. 84		Loc. 85		Loc. 86		Loc. 87		Loc. 88		Loc. 89		Loc. 90		Loc. 91		Loc. 92		Loc. 93		Loc. 94		Loc. 95		Loc. 96		Loc. 97		Loc. 98		Loc. 99		Loc. 100		Loc. 101		Loc. 102		Loc. 103		Loc. 104		Loc. 105		Loc. 106		Loc. 107		Loc. 108		Loc. 109		Loc. 110		Loc. 111		Loc. 112		Loc. 113		Loc. 114		Loc. 115		Loc. 116		Loc. 117		Loc. 118		Loc. 119		Loc. 120		Loc. 121		Loc. 122		Loc. 123		Loc. 124		Loc. 125		Loc. 126		Loc. 127		Loc. 128		Loc. 129		Loc. 130		Loc. 131		Loc. 132		Loc. 133		Loc. 134		Loc. 135		Loc. 136		Loc. 137		Loc. 138		Loc. 139		Loc. 140		Loc. 141		Loc. 142		Loc. 143		Loc. 144		Loc. 145		Loc. 146		Loc. 147		Loc. 148		Loc. 149		Loc. 150		Loc. 151		Loc. 152		Loc. 153		Loc. 154		Loc. 155		Loc. 156		Loc. 157		Loc. 158		Loc. 159		Loc. 160		Loc. 161		Loc. 162		Loc. 163		Loc. 164		Loc. 165		Loc. 166		Loc. 167		Loc. 168		Loc. 169		Loc. 170		Loc. 171		Loc. 172		Loc. 173		Loc. 174		Loc. 175		Loc. 176		Loc. 177		Loc. 178		Loc. 179		Loc. 180		Loc. 181		Loc. 182		Loc. 183		Loc. 184		Loc. 185		Loc. 186		Loc. 187		Loc. 188		Loc. 189		Loc. 190		Loc. 191		Loc. 192		Loc. 193		Loc. 194		Loc. 195		Loc. 196		Loc. 197		Loc. 198		Loc. 199		Loc. 200		Loc. 201		Loc. 202		Loc. 203		Loc. 204		Loc. 205		Loc. 206		Loc. 207		Loc. 208		Loc. 209		Loc. 210		Loc. 211		Loc. 212		Loc. 213		Loc. 214		Loc. 215		Loc. 216		Loc. 217		Loc. 218		Loc. 219		Loc. 220		Loc. 221		Loc. 222		Loc. 223		Loc. 224		Loc. 225		Loc. 226		Loc. 227		Loc. 228		Loc. 229		Loc. 230		Loc. 231		Loc. 232		Loc. 233		Loc. 234		Loc. 235		Loc. 236		Loc. 237		Loc. 238		Loc. 239		Loc. 240		Loc. 241		Loc. 242		Loc. 243		Loc. 244		Loc. 245		Loc. 246		Loc. 247		Loc. 248		Loc. 249		Loc. 250		Loc. 251		Loc. 252		Loc. 253		Loc. 254		Loc. 255		Loc. 256		Loc. 257		Loc. 258		Loc. 259		Loc. 260		Loc. 261		Loc. 262		Loc. 263		Loc. 264		Loc. 265		Loc. 266		Loc. 267		Loc. 268		Loc. 269		Loc. 270		Loc. 271		Loc. 272		Loc. 273		Loc. 274		Loc. 275		Loc. 276		Loc. 277		Loc. 278		Loc. 279		Loc. 280		Loc. 281		Loc. 282		Loc. 283		Loc. 284		Loc. 285		Loc. 286		Loc. 287		Loc. 288		Loc. 289		Loc. 290		Loc. 291		Loc. 292		Loc. 293		Loc. 294		Loc. 295		Loc. 296		Loc. 297		Loc. 298		Loc. 299		Loc. 300		Loc. 301		Loc. 302		Loc. 303		Loc. 304		Loc. 305		Loc. 306		Loc. 307		Loc. 308		Loc. 309		Loc. 310		Loc. 311		Loc. 312		Loc. 313		Loc. 314		Loc. 315		Loc. 316		Loc. 317		Loc. 318		Loc. 319		Loc. 320		Loc. 321		Loc. 322		Loc. 323		Loc. 324		Loc. 325		Loc. 326		Loc. 327		Loc. 328		Loc. 329		Loc. 330		Loc. 331		Loc. 332		Loc. 333		Loc. 334		Loc. 335		Loc. 336		Loc. 337		Loc. 338		Loc. 339		Loc. 340		Loc. 341		Loc. 342		Loc. 343		Loc. 344		Loc. 345		Loc. 346		Loc. 347		Loc. 348		Loc. 349		Loc. 350		Loc. 351		Loc. 352		Loc. 353		Loc. 354		Loc. 355		Loc. 356		Loc. 357		Loc. 358		Loc. 359		Loc. 360		Loc. 361		Loc. 362		Loc. 363		Loc. 364		Loc. 365		Loc. 366		Loc. 367		Loc. 368		Loc. 369		Loc. 370		Loc. 371		Loc. 372		Loc. 373		Loc. 374		Loc. 375		Loc. 376		Loc. 377		Loc. 378		Loc. 379		Loc. 380		Loc. 381		Loc. 382		Loc. 383		Loc. 384		Loc. 385		Loc. 386		Loc. 387		Loc. 388		Loc. 389		Loc. 390		Loc. 391		Loc. 392		Loc. 393		Loc. 394		Loc. 395		Loc. 396		Loc. 397		Loc. 398		Loc. 399		Loc. 400		Loc. 401		Loc. 402		Loc. 403		Loc. 404		Loc. 405		Loc. 406		Loc. 407		Loc. 408		Loc. 409		Loc. 410		Loc. 411		Loc. 412		Loc. 413		Loc. 414		Loc. 415		Loc. 416		Loc. 417		Loc. 418		Loc. 419		Loc. 420		Loc. 421		Loc. 422		Loc. 423		Loc. 424		Loc. 425		Loc. 426		Loc. 427		Loc. 428		Loc. 429		Loc. 430		Loc. 431		Loc. 432		Loc. 433		Loc. 434		Loc. 435		Loc. 436		Loc. 437		Loc. 438		Loc. 439		Loc. 440		Loc. 441		Loc. 442		Loc. 443		Loc. 444		Loc. 445		Loc. 446		Loc. 447		Loc. 448		Loc. 449		Loc. 450		Loc. 451		Loc. 452		Loc. 453		Loc. 454		Loc. 455		Loc. 456		Loc. 457		Loc. 458		Loc. 459		Loc. 460		Loc. 461		Loc. 462		Loc. 463		Loc. 464		Loc. 465		Loc. 466		Loc. 467		Loc. 468		Loc. 469		Loc. 470		Loc. 471		Loc. 472		Loc. 473		Loc. 474		Loc. 475		Loc. 476		Loc. 477		Loc. 478		Loc. 479		Loc. 480		Loc. 481		Loc. 482		Loc. 483		Loc. 484		Loc. 485		Loc. 486		Loc. 487		Loc. 488		Loc. 489		Loc. 490		Loc. 491		Loc. 492		Loc. 493		Loc. 494		Loc. 495		Loc. 496		Loc. 497		Loc. 498		Loc. 499		Loc. 500		Loc. 501		Loc. 502		Loc. 503		Loc. 504		Loc. 505		Loc. 506		Loc. 507		Loc. 508		Loc. 509		Loc. 510		Loc. 511		Loc. 512		Loc. 513		Loc. 514		Loc. 515		Loc. 516		Loc. 517		Loc. 518		Loc. 519		Loc. 520		Loc. 521		Loc. 522		Loc. 523		Loc. 524		Loc. 525		Loc. 526		Loc. 527		Loc. 528		Loc. 529		Loc. 530		Loc. 531		Loc. 532		Loc. 533		Loc. 534		Loc. 535		Loc. 536		Loc. 537		Loc. 538		Loc. 539		Loc. 540		Loc. 541		Loc. 542		Loc. 543		Loc. 544		Loc. 545		Loc. 546		Loc. 547		Loc. 548		Loc. 549		Loc. 550		Loc. 551		Loc. 552		Loc. 553		Loc. 554		Loc. 555		Loc. 556		Loc. 557		Loc. 558		Loc. 559		Loc. 560		Loc. 561		Loc. 562		Loc. 563		Loc. 564		Loc. 565		Loc. 566		Loc. 567		Loc. 568		Loc. 569		Loc. 570		Loc. 571		Loc. 572		Loc. 573		Loc. 574		Loc. 575		Loc. 576		Loc. 577		Loc. 578		Loc. 579		Loc. 580		Loc. 581		Loc. 582		Loc. 583		Loc. 584		Loc. 585		Loc. 586		Loc. 587		Loc. 588		Loc. 589		Loc. 590		Loc. 591		Loc. 592		Loc. 593		Loc. 594		Loc. 595		Loc. 596		Loc. 597		Loc. 598		Loc. 599		Loc. 600		Loc. 601		Loc. 602		Loc. 603		Loc. 604		Loc. 605		Loc. 606		Loc. 607		Loc. 608		Loc. 609		Loc. 610		Loc. 611		Loc. 612		Loc. 613		Loc. 614		Loc. 615		Loc. 616		Loc. 617		Loc. 618		Loc. 619		Loc. 620		Loc. 621		Loc. 622		Loc. 623		Loc. 624		Loc. 625		Loc. 626		Loc. 627		Loc. 628		Loc. 629		Loc. 630		Loc. 631		Loc. 632		Loc. 633		Loc. 634		Loc. 635		Loc. 636		Loc. 637		Loc. 638		Loc. 639		Loc. 640		Loc. 641		Loc. 642		Loc. 643		Loc. 644		Loc. 645		Loc. 646		Loc. 647		Loc. 648		Loc. 649		Loc. 650		Loc. 651		Loc. 652		Loc. 653		Loc. 654		Loc. 655		Loc. 656		Loc. 657		Loc. 658		Loc. 659		Loc. 660		Loc. 661		Loc. 662		Loc. 663		Loc. 664		Loc. 665		Loc. 666		Loc. 667		Loc. 668		Loc. 669		Loc. 670		Loc. 671		Loc. 672		Loc. 673		Loc. 674		Loc. 675		Loc. 676		Loc. 677		Loc. 678		Loc. 679		Loc. 680		Loc. 681		Loc. 682		Loc. 683		Loc. 684		Loc. 685		Loc. 686		Loc. 687		Loc. 688		Loc. 689		Loc. 690		Loc. 691		Loc. 692		Loc. 693		Loc. 694		Loc. 695		Loc. 696		Loc. 697		Loc. 698		Loc. 699		Loc. 700		Loc. 701		Loc. 702		Loc. 703		Loc. 704		Loc. 705		Loc. 706		Loc. 707		Loc. 708		Loc. 709		Loc. 710		Loc. 711		Loc. 712		Loc. 713		Loc. 714		Loc. 715		Loc. 716		Loc. 717		Loc. 718		Loc. 719		Loc. 720		Loc. 721		Loc. 722		Loc. 723		Loc. 724		Loc. 725		Loc. 726		Loc. 727		Loc. 728		Loc. 729		Loc. 730		Loc. 731		Loc. 732		Loc. 733		Loc. 734		Loc. 735		Loc. 736		Loc. 737		Loc. 738		Loc. 739		Loc. 740		Loc. 741		Loc. 742		Loc. 743		Loc. 744		Loc. 745		Loc. 746		Loc. 747		Loc. 748		Loc. 749		Loc. 750		Loc. 751		Loc. 752		Loc. 753		Loc. 754		Loc. 755		Loc. 756		Loc. 757		Loc. 758		Loc. 759		Loc. 760		Loc. 761		Loc. 762		Loc. 763		Loc. 764		Loc. 765		Loc. 766		Loc. 767		Loc. 768		Loc. 769		Loc. 770		Loc. 771		Loc. 772		Loc. 773		Loc. 774		Loc. 775		Loc. 776		Loc. 777		Loc. 778		Loc. 779		Loc. 780		Loc. 781		Loc. 782		Loc. 783		Loc. 784		Loc. 785		Loc. 786		Loc. 787		Loc. 788		Loc. 789		Loc. 790		Loc. 791		Loc. 792		Loc. 793		Loc. 794		Loc. 795		Loc. 796		Loc. 797		Loc. 798		Loc. 799		Loc. 800		Loc. 801		Loc. 802		Loc. 803		Loc. 804		Loc. 805		Loc. 806		Loc. 807		Loc. 808		Loc. 809		Loc. 810		Loc. 811		Loc. 812		Loc. 813		Loc. 814		Loc. 815		Loc. 816		Loc. 817		Loc. 818		Loc. 819		Loc. 820		Loc. 821		Loc. 822		Loc. 823		Loc. 824		Loc. 825		Loc. 826		Loc. 827		Loc. 828		Loc. 829		Loc. 830		Loc. 831		Loc. 832		Loc. 833		Loc. 834		Loc. 835		Loc. 836		Loc. 837		Loc. 838		Loc. 839		Loc. 840		Loc. 841		Loc. 842		Loc. 843		Loc. 844		Loc. 845		Loc. 846		Loc. 847		Loc. 848		Loc. 849		Loc. 850		Loc. 851		Loc. 852		Loc. 853		Loc. 854		Loc. 855		Loc. 856		Loc. 857		Loc. 858		Loc. 859		Loc. 860		Loc. 861		Loc. 862		Loc. 863		Loc. 864		Loc. 865		Loc. 866		Loc. 867		Loc. 868		Loc. 869		Loc. 870		Loc. 871		Loc. 872		Loc. 873		Loc. 874		Loc. 875		Loc. 876		Loc. 877		Loc. 878		Loc. 879		Loc. 880		Loc. 881		Loc. 882		Loc. 883		Loc. 884		Loc. 885		Loc. 886		Loc. 887		Loc. 888		Loc. 889		Loc. 890		Loc. 891	
--------------	--------	--	--------	--	--------	--	--------	--	--------	--	--------	--	--------	--	--------	--	--------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	---------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--	----------	--

The standard deviations do not improve to any degree over the no-anomaly case. It is believed that the reason for the poor results is that a simple linear anomaly function is not sufficient for locating across the Aleutians. However, as we progressed from the no-anomaly case, through the LONG SHOT anomaly and the linear functional anomaly cases, the average of shifts from the mean (Tables VI, VIII and IX) changes from 12.3 to 10.5 to 5.6 km, indicating steady improvement. We are now ready to introduce additional constraints to improve consistency.

Fox 1/LONG SHOT anomalies

If the anomaly functions derived are constrained by two events, rather than just LONG SHOT, even though the second event is known to be mislocated, a set of functions (again linear) can be used to try to attain consistency, at least for events between the constraints.

In order to cover as large an area as possible, Fox-1 and LONG SHOT are used as the constraining events. The linear functional anomalies for the stations are shown in Figures 16a and 16b. The results obtained by applying these Fox-1/LONG SHOT anomalies as corrections are plotted in Figure 17 and are summarized in Table X. The clustering for the events from Fox-2 to Fox-8 is seen to converge slightly, but the other events are poor indeed. Andreanof-11, in particular, still appears to be unusual in that even though it is adjacent to LONG SHOT, the clustering is about the worst of any event. As expected, the clustering in the Fox Islands, except for Fox-2, is slightly improved over the previous case, but in the Near Islands, the clustering is noticeably worse than in any other case heretofore. The reason for this is that the linear constraint provided by Fox-1 and LONG SHOT does not even grossly approximate the anomalies one should be using in the Near Islands. However,

TABLE X
LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (COEFF. FROM THE PLATE) OBTAINED BY
APPLYING FOX-17118 SHOT FUNCTIONAL ANALYSIS

[illegible]

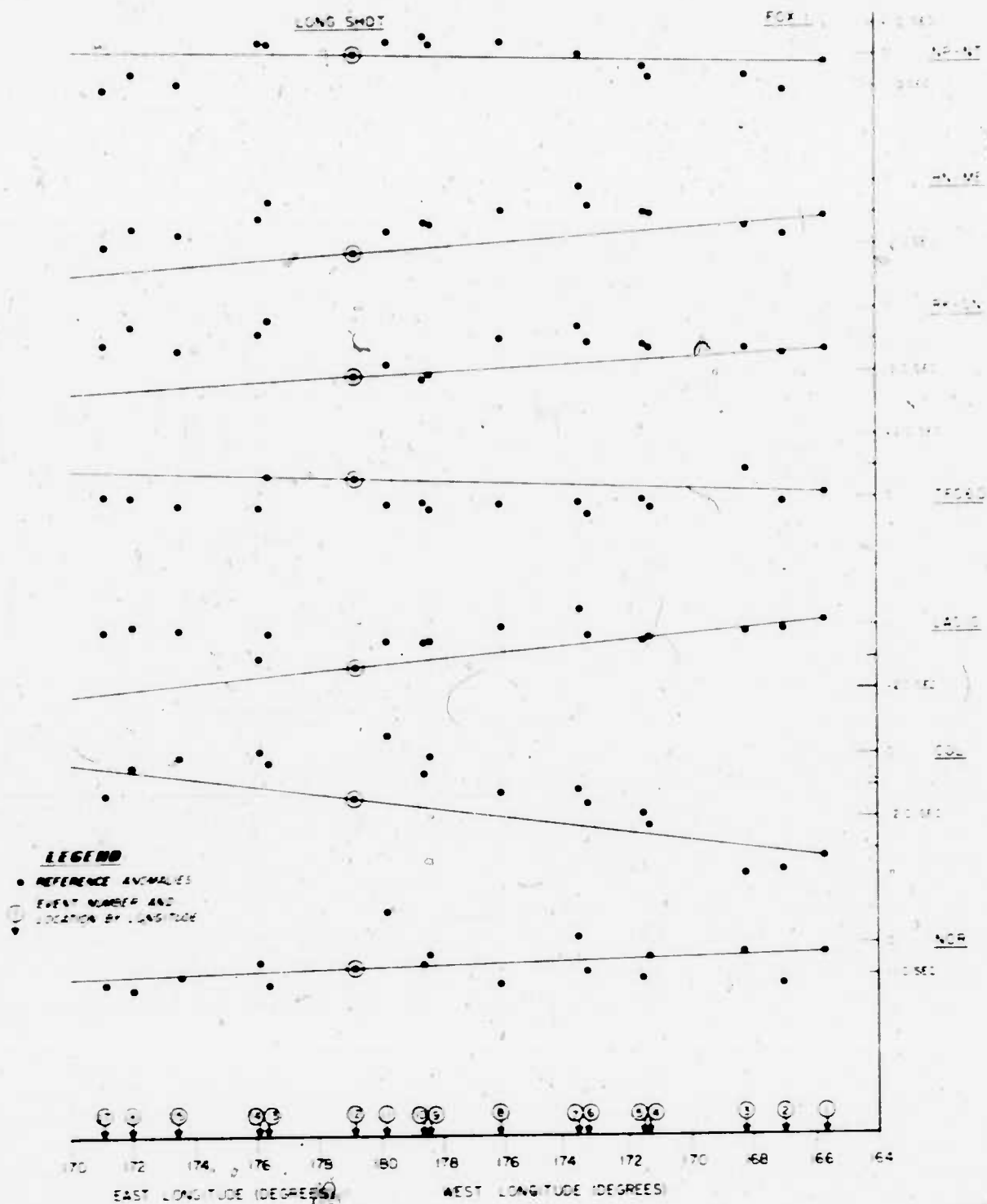


Figure 16a. Determination of FOX-1/LONG SHOT functional anomalies.

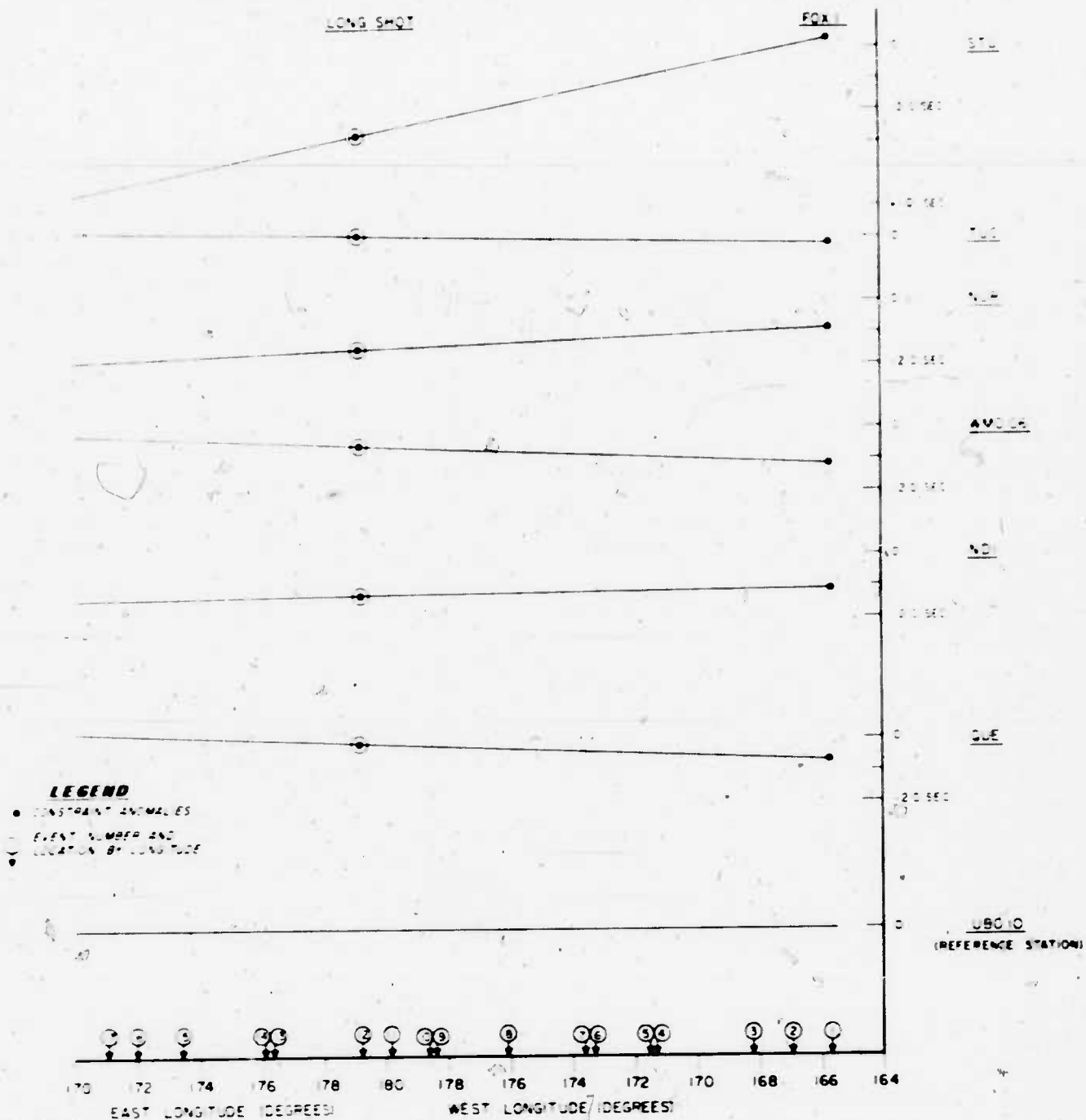


Figure 16b. Determination of FOX-1/LONG SHOT functional anomalies.

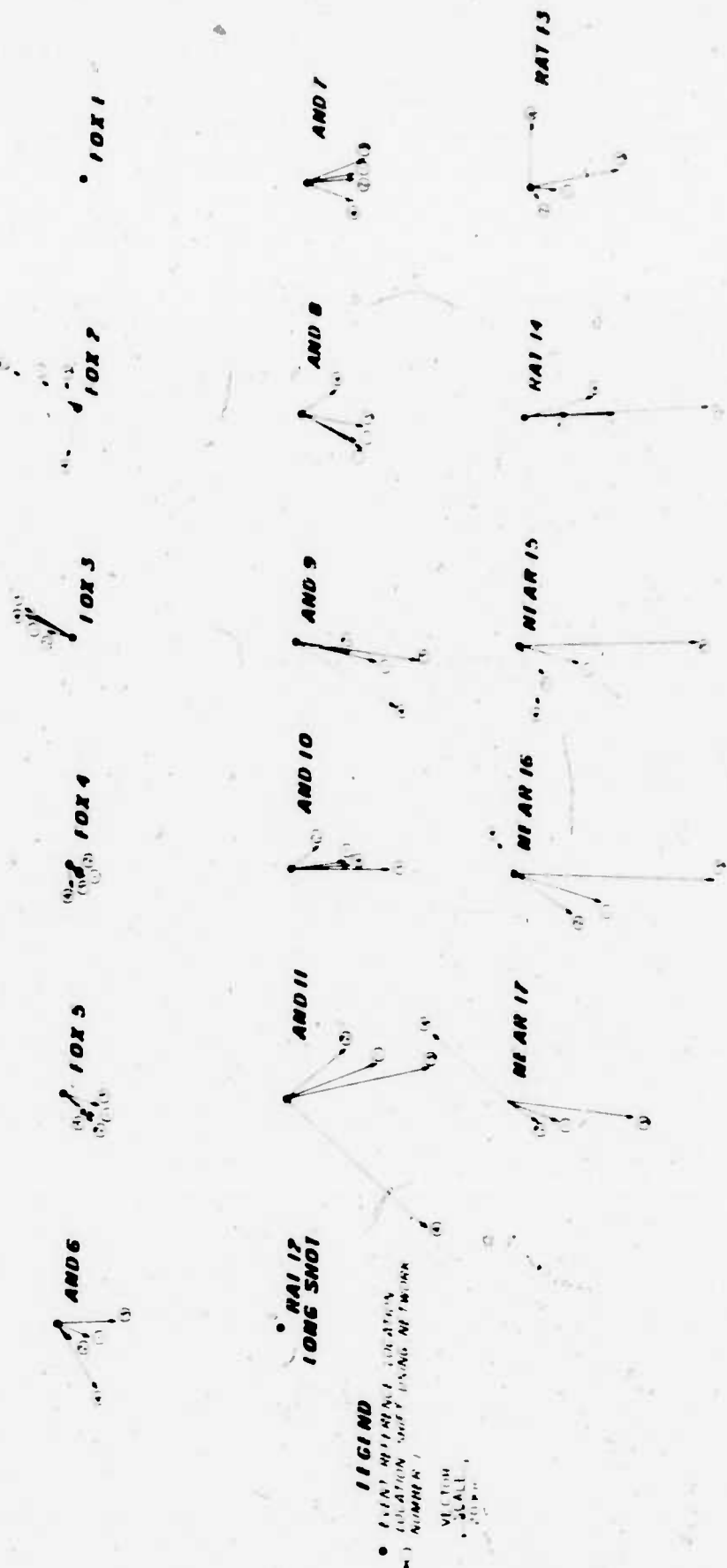


Figure 17. Location shifts for four networks obtained by applying FOX-1/LONG SHOT functional anomalies.

the standard deviations are remarkably improved through the Fox and Andreanof Islands, generally by a factor of about two. Therefore, using two widely separated events as constraints, the least-squares fits and the network clustering of events between the two are better than if no anomalies, constant anomalies, or single-constraint linear functional anomalies had been applied.

In order to gain location control in the Near Islands, and to improve the locations in the Andreanof Islands, two additional constraints can be imposed, one in each of the two regions.

FARN anomalies

Because the anomalies are neither constant nor linear across the entire Aleutian region, a set of anomaly functions can be derived which are (1) constrained by the anomalies computed from four assumed-correct events (Fox-1, Andreanof-6, LONG SHOT, and Near-17) and (2) piecewise linear between the four constraints. A plot of the functions, referred to as "FARN" (for Fox-Andreanof-Rat-Near), is shown in Figures 18a and 18b.

The location shifts obtained by applying the FARN anomalies are shown in Figure 19. The scatter of the clustered locations for each event is reduced and is now about the same across the entire Aleutian region, except for Near-15 and Andreanof-11. Even for these two events, if Network 4 is not included, the clustering approaches the average. It can be expected that Network 4 will be unstable due to its small aperture of about 59° where the effect of small reading errors is exaggerated. A summary of the results is given in Table XI, where all of the standard deviations become less than 0.5 seconds, most being less than 0.35 seconds. The clustering error is about 8 km, and without Network 4 being considered for Andreanof-11 and Near-15, it is about 6 km.

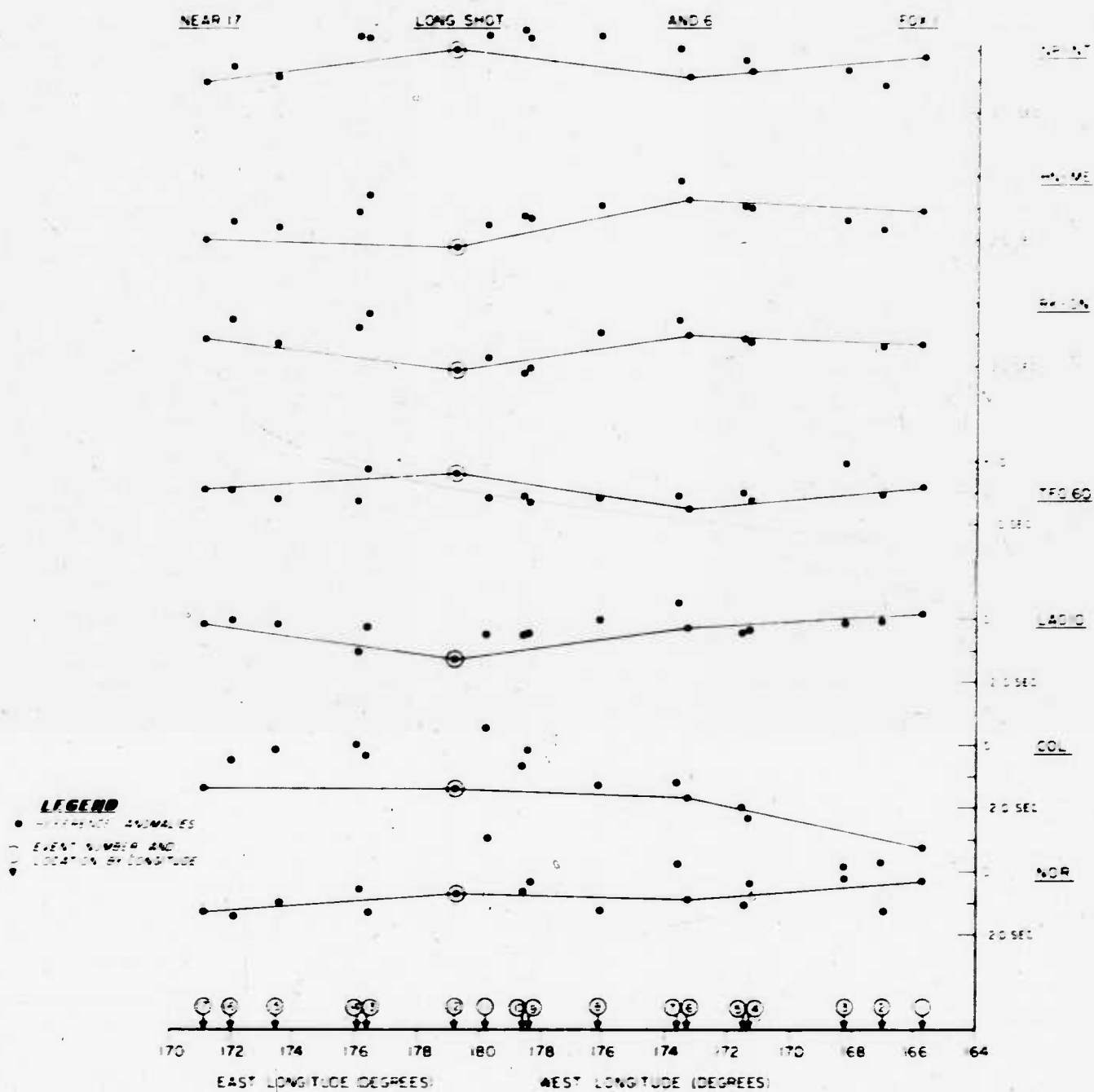


Figure 18a. Determination of anomalies using Fox, Andreanof, Rat, and Near (FARN) constraining events.

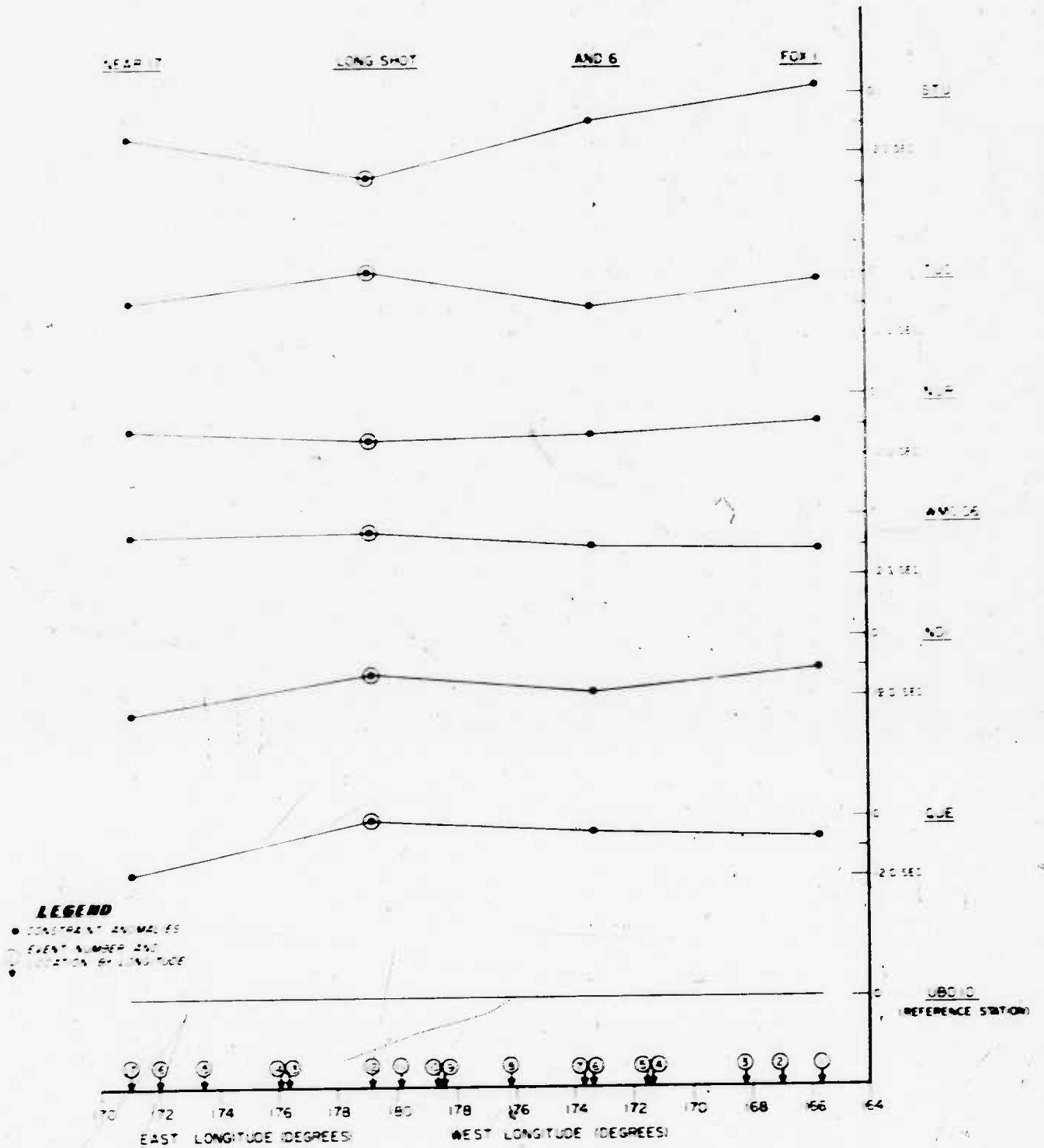


Figure 18b. Determination of anomalies using Fox, Andreanof, Rat, and Near (FARN) constraining events.

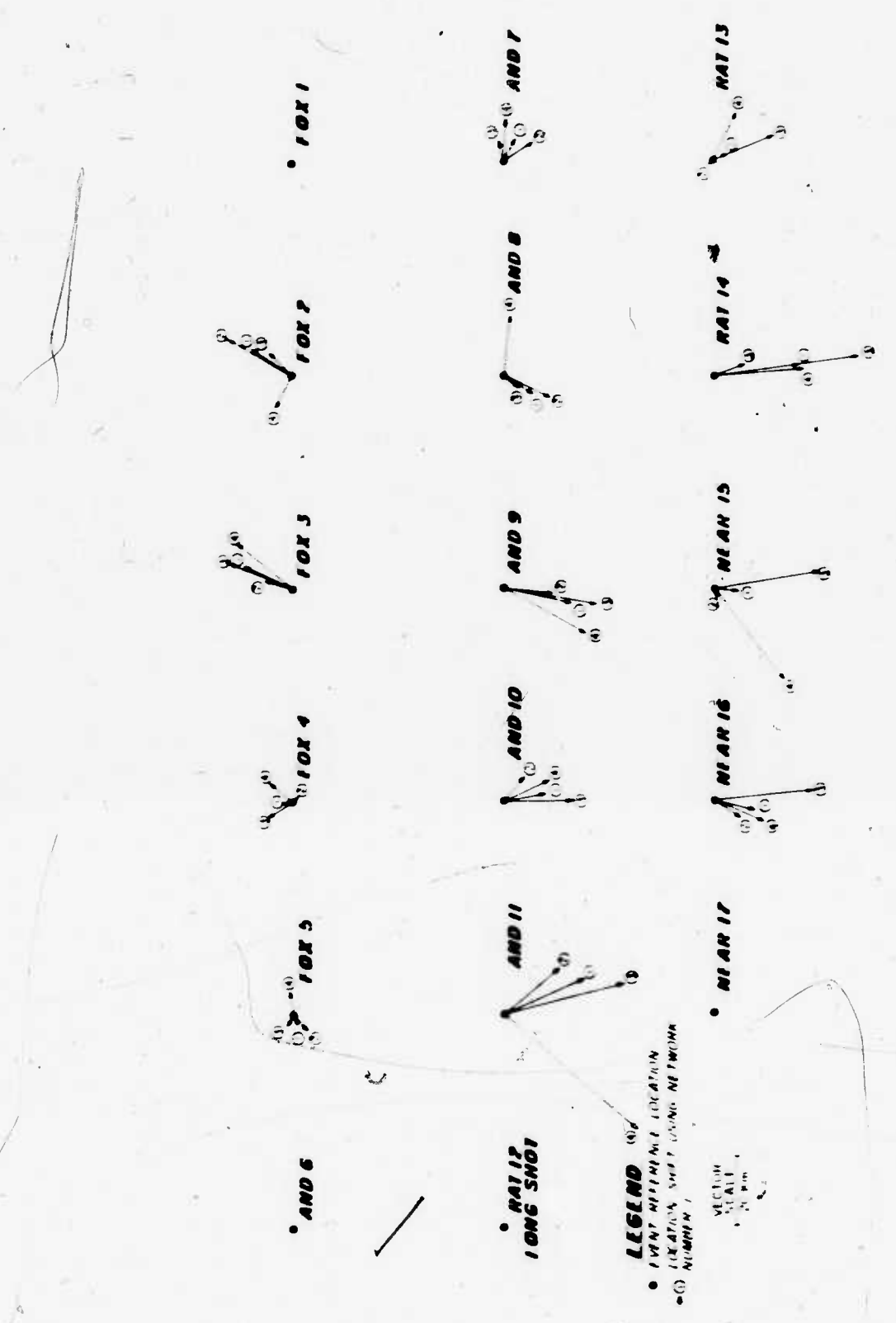


Figure 19. Location shifts for four networks obtained by applying FARN (see text) anomalies.

TABLE XI
LOCATION SHIFTS, STANDARD DEVIATIONS (), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) DETERMINED BY
APPLYING FAHJ FUNCTIONAL ANOMALIES

Network	Loc 1			Loc 2			Loc 3			Loc 4			Loc 5			Loc 6			Loc 7			Loc 8			Loc 9		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()
1	00	00	00	15.9	30.1	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
2	00	00	00	21.5	34.5	11.2	8.6	33.0	5.0	19.4	31.2	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
3	00	00	00	10.1	18.6	1.8	19.4	31.2	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
4	00	00	00	10.8	17.0	11.1	21.1	35.5	6.2	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
Mean	00	00	00	11.1	23.1	8.6	16.2	33.0	4.8	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0

Network	Mid 10			Mid 11			Mid 12			Mid 13			Mid 14			Mid 15			Mid 16			Mid 17			Average of Shifts from Mean		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()	From Input	From Mean	()
1	15.1	18.3	3.2	25.5	30.5	10.4	00	00	00	4.2	38.1	2.2	20.8	35.1	5.6	15.6	35.6	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
2	10.0	10.4	0.4	20.9	31.2	17.0	00	00	00	1.5	38.6	10.8	10.0	35.5	15.0	15.6	35.6	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
3	20.6	24.2	3.6	25.8	30.1	10.8	00	00	00	19.0	39.3	8.8	4.6	39.4	15.8	30.8	35.6	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
4	15.1	18.3	3.2	19.2	29.5	11.4	00	00	00	15.0	35.9	8.8	2.0	39.5	15.1	15.6	35.6	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0
Mean	14.8	18.2	3.4	23.8	31.8	18.3	00	00	00	9.0	38.0	8.9	25.1	35.1	9.1	18.1	35.6	4.0	15.5	35.5	4.0	15.5	35.5	4.0	15.5	35.5	4.0

The principal drawback to using the FARN anomalies is that the location of LONG SHOT is accurately known but the locations of the other constraining events are not known at all. Mixing the two kinds of anomalies from which the functions are derived may achieve consistency, but there is no way of estimating the accuracy of the relative locations of the events. Furthermore, the earthquakes used as constraints may be grossly (30-50 km) mislocated and there is no way of knowing the effect of this on the technique. (It will be shown later in this report that the effect is not great for a theoretical case.) Therefore, our next step will be to determine the anomaly functions by neglecting the true LONG SHOT anomalies and using instead those computed from the reported seismic location.

Fiducial functional anomalies

Since it is known that the Aleutian Islands events have a large bias in their locations (as evidenced by locating LONG SHOT with a 329-station four-quadrant network and subsets thereof), it can be safely assumed that the true position of LONG SHOT is "mislocated" relative to any of the seismic locations of earthquakes throughout the region from the Fox Islands to the Near Islands. Therefore, if the seismic location of LONG SHOT reported by Lambert et al., (1969) is taken to be the reported location of just another Rat Island event, the anomalies from this fiducial location (21 km in error) can be computed and compared to the anomalies from the Adjusted seismic locations of earthquakes. A set of fiducial functional anomalies can then be fitted, without constraints, to all of the observed anomalies. The only requirement on the functions is that they be piecewise linear; the number of linear segments derived for all of the stations varies from two to three. The anomaly plots and the fiducial functions for the stations are

shown in Figures 20a and 20b. The observed true LONG SHOT anomalies are included for comparison. Significantly, for every station, the fiducial LONG SHOT anomaly agrees much better than the true anomaly with the earthquake anomalies, which supports the hypothesis that the Aleutian Islands earthquakes in the vicinity of LONG SHOT are mislocated in a similar way.

If the functions in Figure 20 are now applied as corrections, the locations obtained with the four networks are shown in Figure 21, and the results summarized in Table XII.

For nine of the events, Network 4 yields a result clearly at variance with the other networks; for Networks 2 and 3, there is one event at variance. Therefore, the results for these cases were not included in forming the average shift from the mean or in forming the "best estimate" of the epicenter. The excluded results are marked with an asterisk on Table XII.

The average shift from either the mean or "best estimate" is about 5.5 km, and for all networks the standard deviations are less than 0.5 sec (except for one result, the standard deviations are all less than 0.34 sec) with the average being less than 0.25 sec, an acceptable value to indicate reading precision. We should note, however that if the events with asterisks are included, then the deviation from the mean is 8.5 kilometers, about the same as for the FARN anomalies.

If anomalies are now computed from the mean epicenters derived above, the results as shown in Figures 22a and 22b indicate that the station anomalies display less scatter from a function than before the shifts.

It is now necessary to correct the anomaly functions for the known LONG SHOT bias and to attempt to smooth them (remove sharp changes) across the Aleutian.

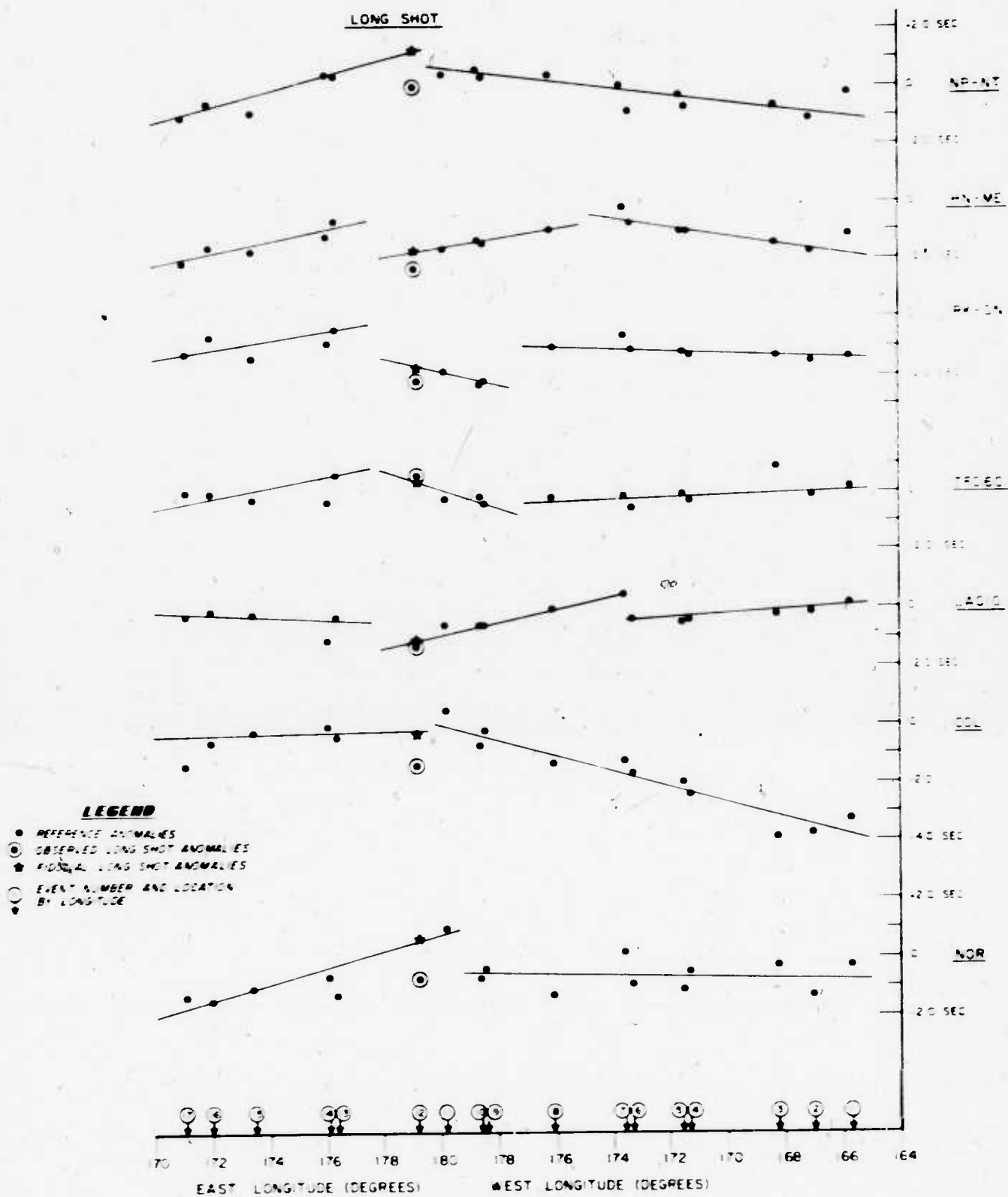


Figure 20a. Functional anomalies determined from fiducial LONG SHOT location.

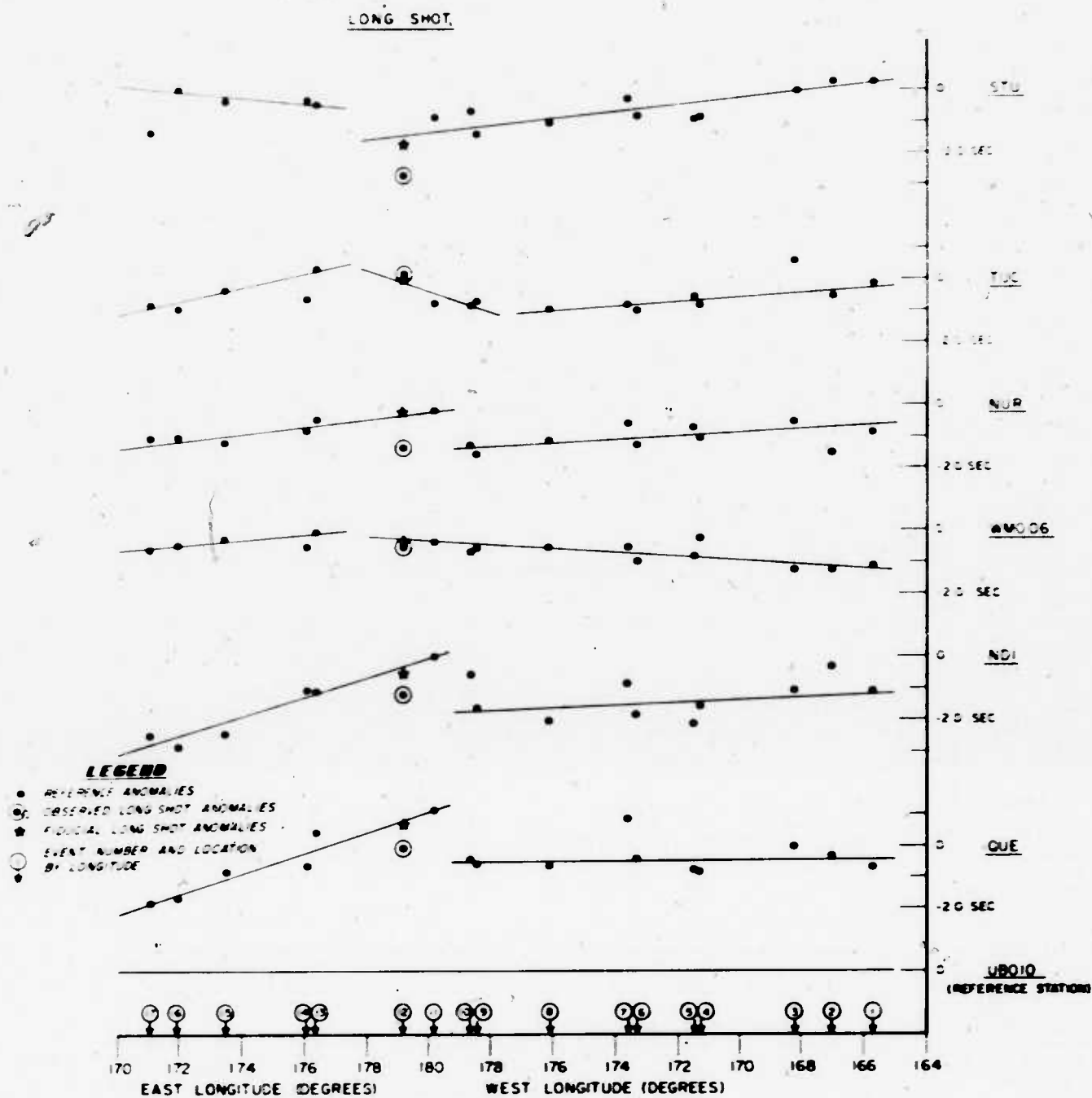


Figure 20b. Functional anomalies determined from fiducial LONG SHOT location.

TABLE XII
LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY
APPLYING FUNCTIONAL ANALYSIS

Network	Loc 1			Loc 2			Loc 3			Loc 4			Loc 5			Loc 6			Loc 7			Loc 8			Loc 9		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input	From Mean	(km)	From Input	From Mean	(km)	From Input	From Mean	(km)	From Input	From Mean	(km)	From Input	From Mean	(km)	From Input	From Mean	(km)	From Input	From Mean	(km)	From Input	From Mean	(km)	From Input	From Mean	(km)
1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Mean	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	

Network	Loc 10			Loc 11			Loc 12			Loc 13			Loc 14			Loc 15			Loc 16			Loc 17			Loc 18			Average of shifts from mean		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From	To	(km)	From	To	(km)	From	To	(km)	From	To	(km)	From	To	(km)	From	To	(km)	From	To	(km)	From	To	(km)	From	To	(km)	From	To	(km)
1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Mean	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	

*Not included in forming mean

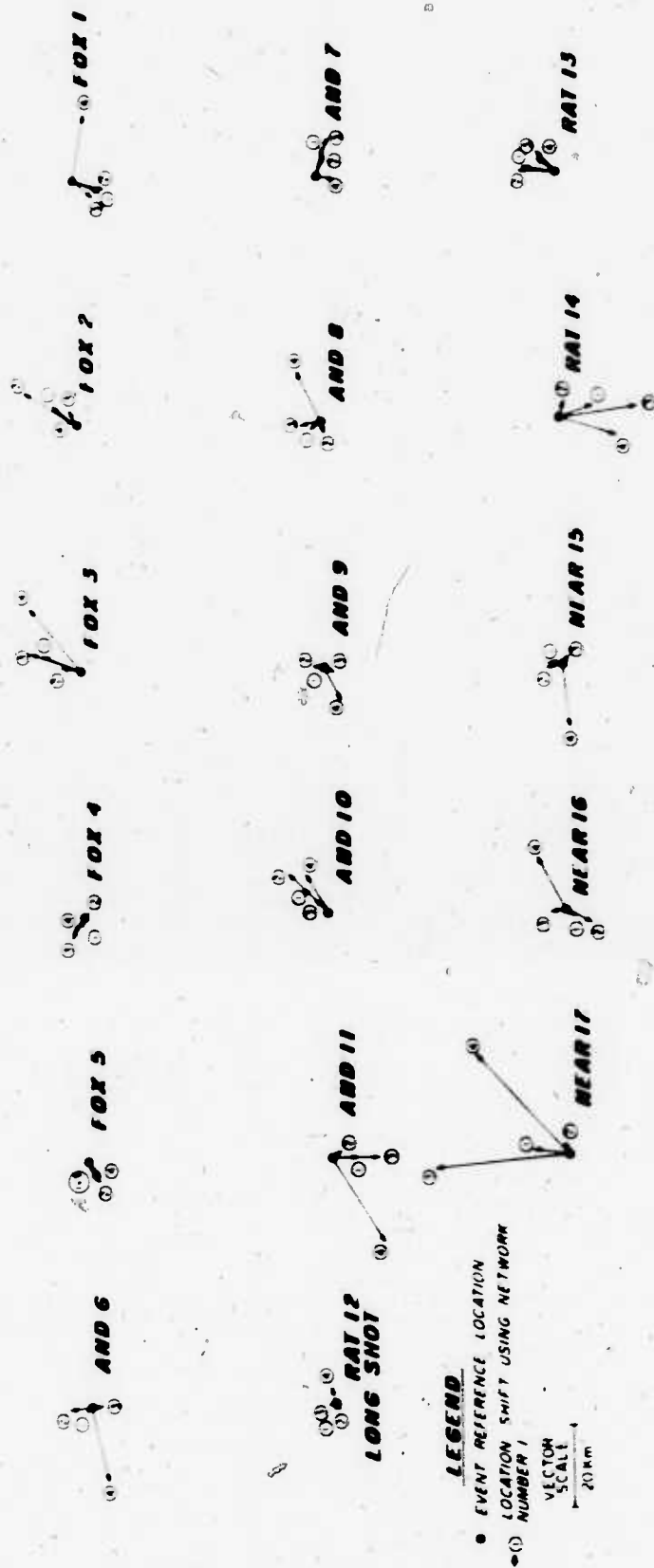


Figure 21. Location shifts for four networks obtained by applying fiducial LONG SHOT functional anomalies.

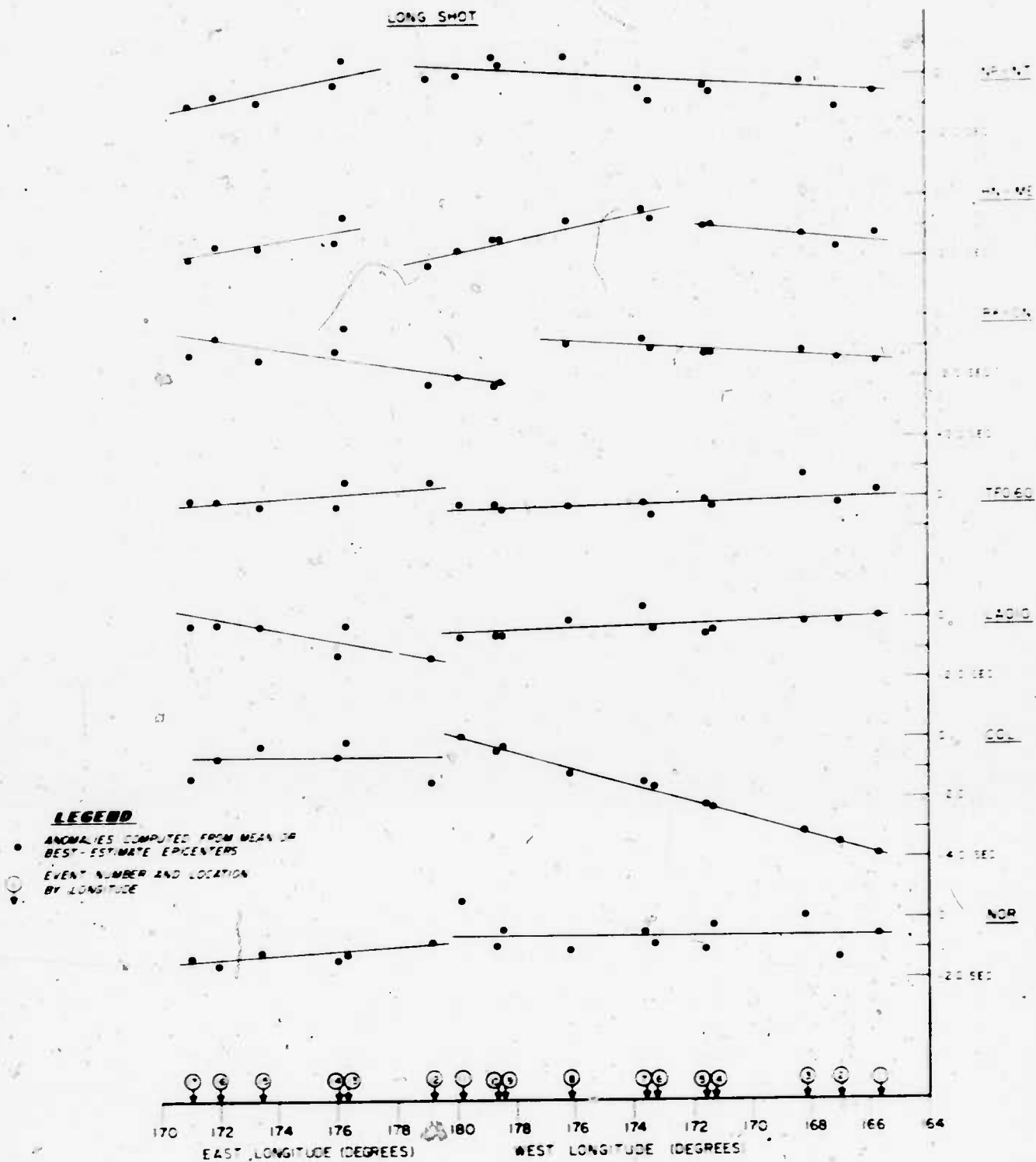


Figure 22a. Anomalies computed from "best estimate" epicenters as determined using fiducial functional anomalies. U

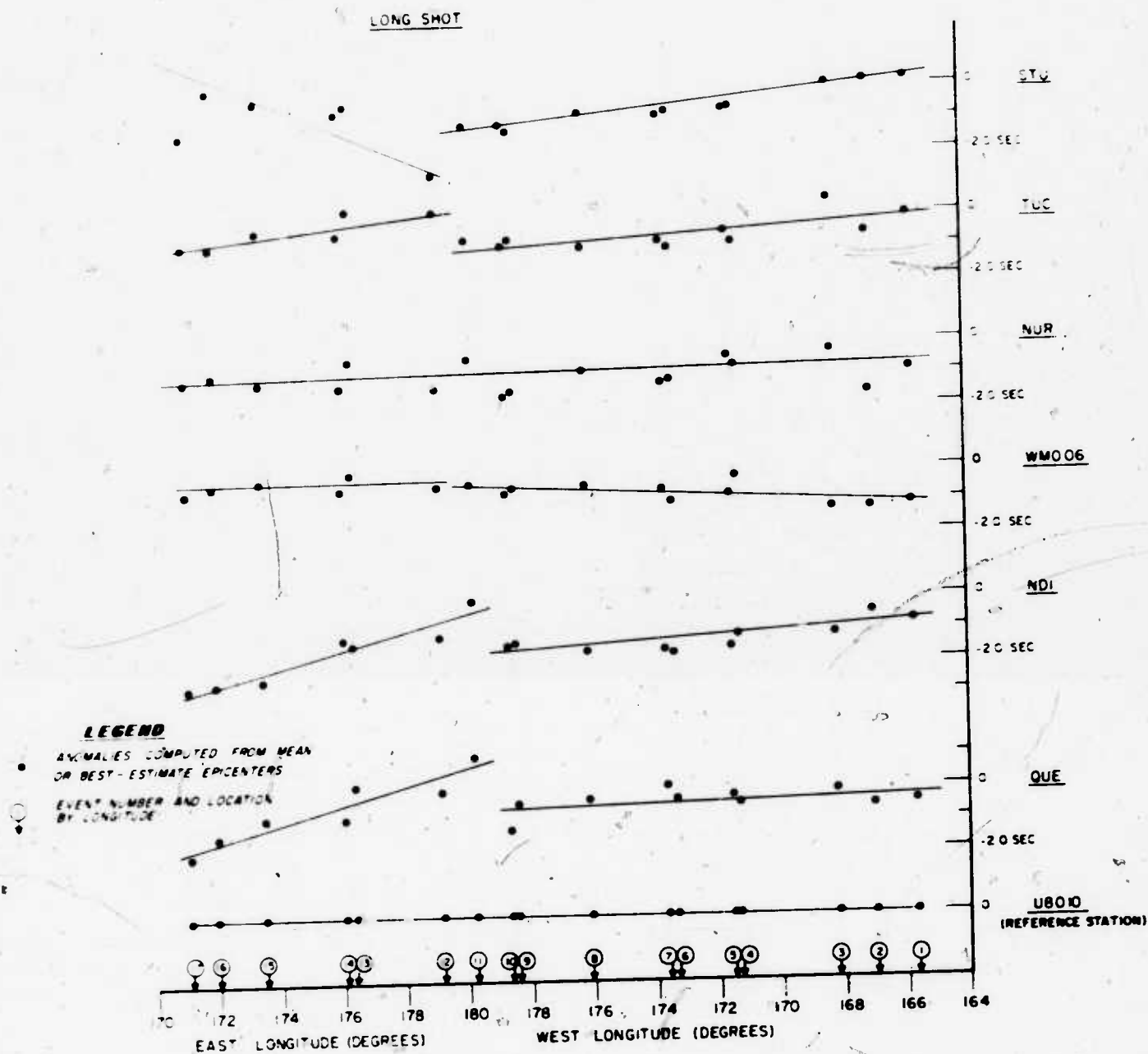


Figure 22b. Anomalies computed from "best estimate" epicenters as determined using fiducial functional anomalies.

Aleutian functional anomalies

Because it is known that LONG SHOT is actually mislocated by 21 km to the north-northwest, we see that to obtain anomalies which yield small absolute location errors LONG SHOT, and to some degree the other events, must be shifted toward the south-east. One would choose to shift them in such a way that the anomaly functions are further smoothed out. One of the guiding observations in determining which events to shift, and by how much, is the apparent "anomaly discontinuity" displayed by many of the stations (especially STU, NDI, QUE, and RK-OK) in the vicinity of 179°W (Andreanof-10 and -11). The reason for this discontinuity is traceable to the original mislocation effect in the Aleutians, but why it exists is presently not known. Another guiding observation is that the only quantitative bias information available is that provided from the LONG SHOT shift, which amounts to 21 km toward the north-northwest. With these guidelines, we choose to shift the positions of all of the events between Andreanof-11 and Near-17 21 km to the south-southeast from their respective "best estimates". All events between Andreanof-10 and Fox-1 were not shifted at all from their "best estimates". The plots of the anomalies computed from the variably shifted locations and the new anomaly functions which result are shown in Figures 23a and 23b. Although the discontinuity remains, it has been reduced, and the functions are slightly more continuous. We choose these "Aleutian functional" anomalies to be the best ones to apply when any combination of stations in Network 1 is used to locate events in the Aleutian Islands region.

The results obtained by applying the Aleutian functional anomalies are shown in Figure 24 for the four networks and are summarized in Table XIII. The corresponding final "best estimates" of the epicenters are given in Table XIV with the shifts from both the original NOS and the Adjusted locations in Table I.

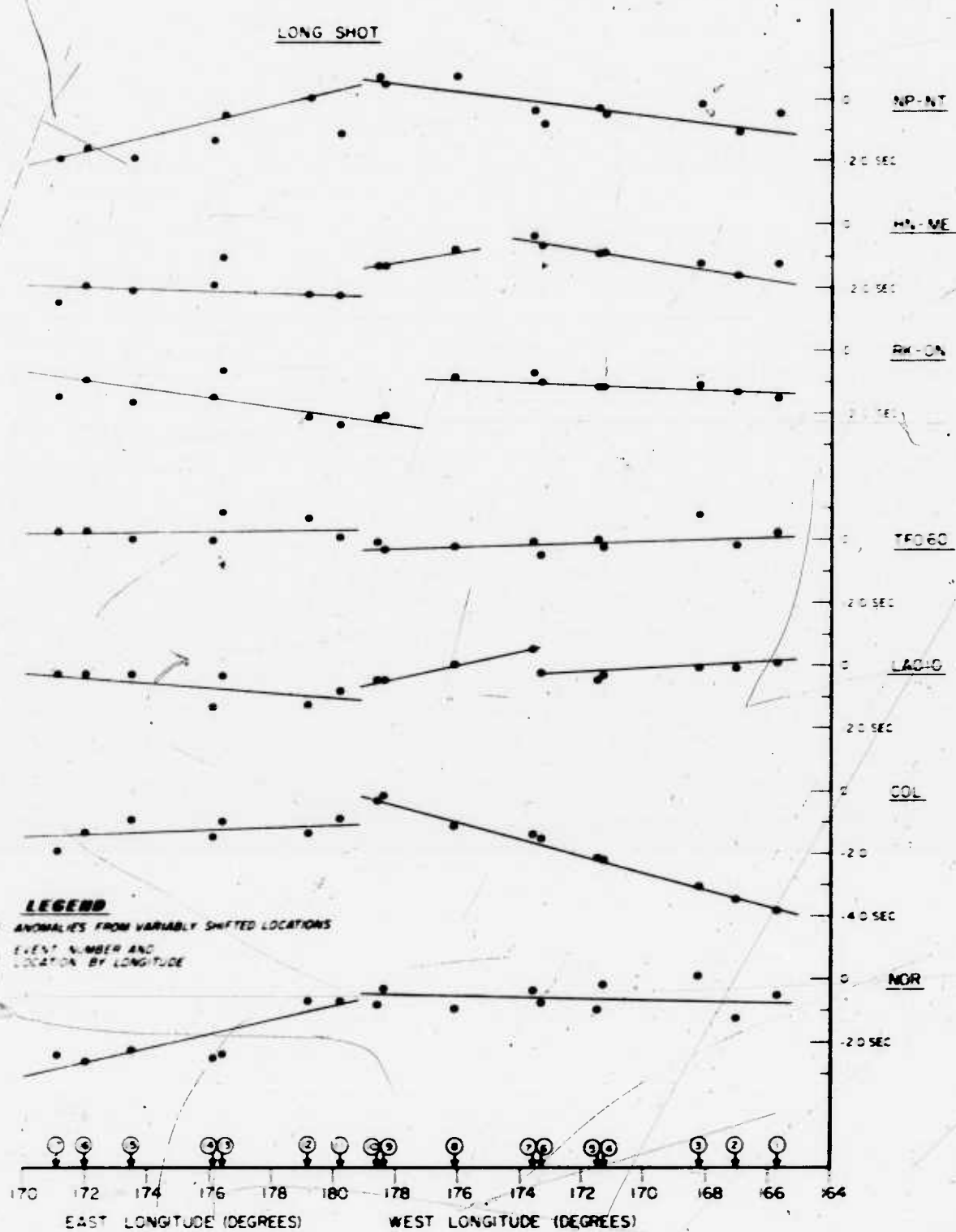


Figure 23a. Determination of Aleutian functional anomalies.

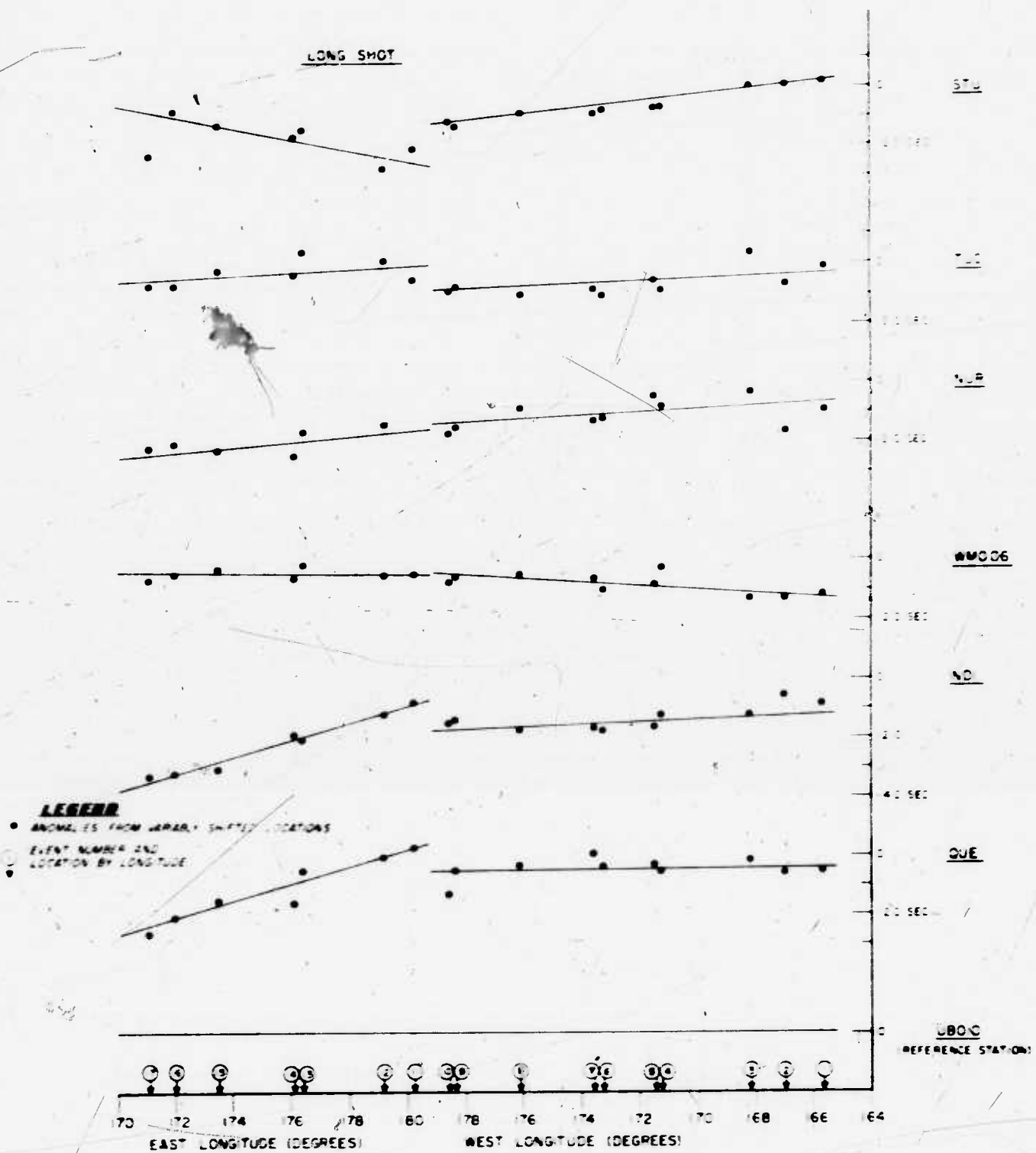


Figure 23b. Determination of Aleutian functional anomalies.

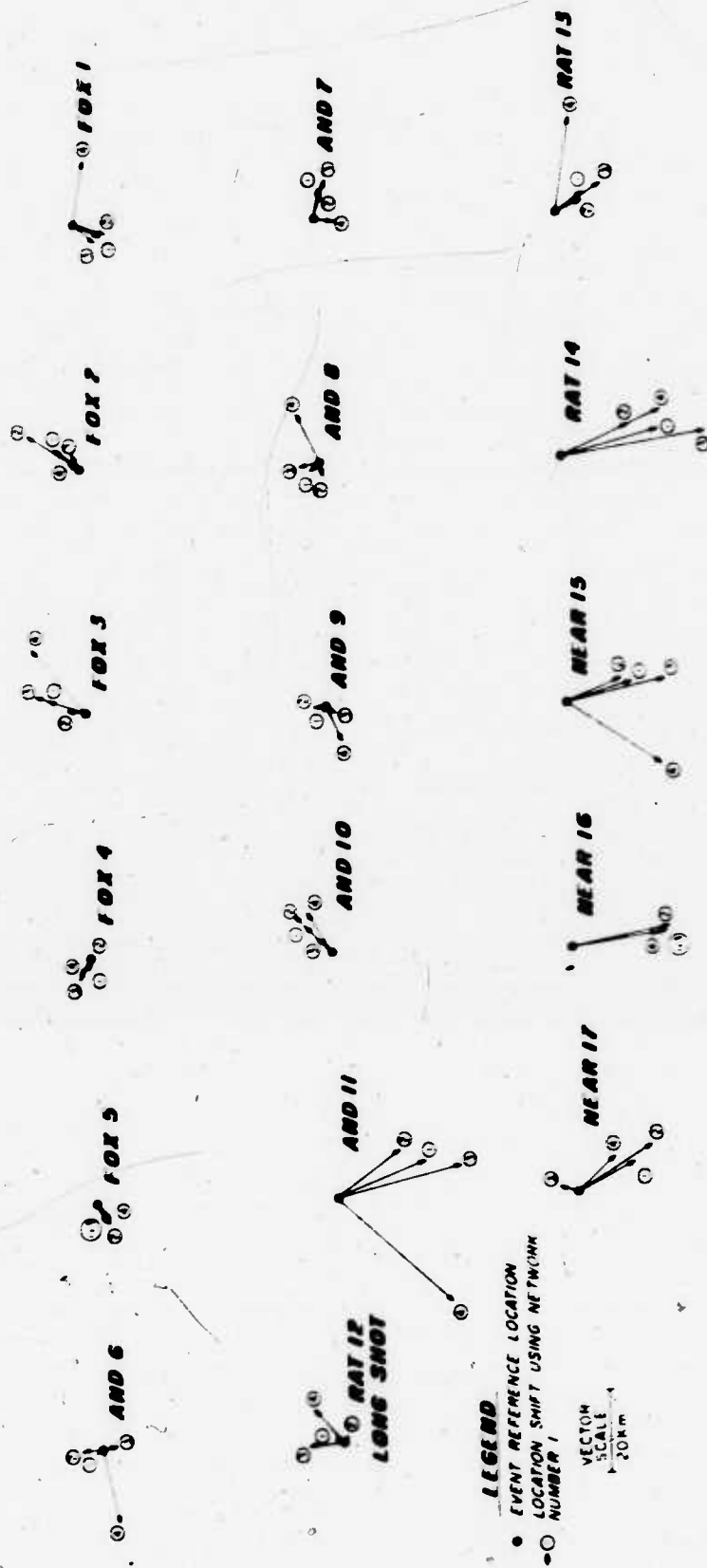


Figure 24. Location shifts for four networks using Aleutian functional anomalies.

TABLE XIII
LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY
APPLYING ALBERTIAN FUNCTIONAL ANOMALIES

Network	Loc. 1			Loc. 2			Loc. 3			Loc. 4			Loc. 5			Loc. 6			Loc. 7			Loc. 8			Loc. 9		
	From	To	Mean	From	To	Mean	From	To	Mean	From	To	Mean	From	To	Mean	From	To	Mean	From	To	Mean	From	To	Mean	From	To	Mean
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Year	Year 11			Year 12			Year 13			Year 14			Year 15			Year 16			Year 17			Average of shifts from mean
	Location shifts			Location shifts			Location shifts			Location shifts			Location shifts			Location shifts			Location shifts			
	From Input (km)	From Output (km)	Mean (km)	From Input (km)	From Output (km)	Mean (km)	From Input (km)	From Output (km)	Mean (km)	From Input (km)	From Output (km)	Mean (km)	From Input (km)	From Output (km)	Mean (km)	From Input (km)	From Output (km)	Mean (km)	From Input (km)	From Output (km)	Mean (km)	
1	8.0	12.0	10.0	3.0	13.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
11	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
12	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
13	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
14	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
15	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
16	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
17	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
18	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	

[illegible]

TABLE XIV
Final Best-Estimates of Event Set Located
with Aleutian Functional Anomalies

Event	Mean or Best-Estimate Locations		Shift From NOS LOCATION km	Shift From Adjusted Location km
	Latitude (Degrees)	Longitude (Degrees)		
Fox 1	53.583 N	165.727 W	12	8
Fox 2	52.743 N	166.931 W	1	5
Fox 3	52.646 N	168.163 W	6	10
Fox 4	52.082 N	171.372 W	8	3
Fox 5	52.008 N	171.535 W	19	6
And 6	51.682 N	175.361 W	8	1
And 7	51.609 N	173.487 W	11	8
And 8	51.402 N	176.121 W	10	4
And 9	51.452 N	178.482 W	5	3
And 10	51.528 N	178.385 W	4	10
And 11	51.088 N	179.628 W	30	26
Long Shot	51.472 N	179.214 E	5	5
Rat 13	51.703 N	176.507 E	14	9
Rat 14	51.663 N	176.196 E	28	27
Near 15	52.292 N	173.621 E	17	19
Near 16	52.670 N	172.114 E	28	24
Near 17	53.004 N	171.217 E	12	17
Average Shift			13	10

Several things have been accomplished with these Aleutian functional anomalies: (1) a tight location cluster (within about 5 km, 8 km if one includes the readings with asterisks) using three or four different networks; (2) acceptably low standard deviations (about 0.25 sec) for all networks and events; and (3) reasonable functional anomalies for each station.

The question persists, though, of the absolute and relative accuracy of location throughout the entire region. The anomaly functions were derived using assumed locations for the events. That these assumed locations are incorrect by an unknown amount is beyond reasonable doubt. However, as long as it is known which events were used to determine the functions, all subsequent events can be referenced to them, almost as if it did not matter what their actual location errors may have been. When and if an event occurs somewhere in the Aleutian Islands other than on Amchitka Island, under conditions such that its location is accurately known, the anomalies can be recomputed and the anomaly functions translated to accommodate the additional constraint. The position of this additional event may be accurately known due to it being another explosion (far away from Amchitka), due to its being recorded by a local high quality network, or due to clear surficial intensity effects (faulting, jointing, etc). The latter criterion can only serve to remove gross bias, because visible effects from earthquakes depend on many factors besides epicentral distance; this is further complicated by the Aleutian Islands region itself, being composed of small and sometimes uninhabited islands, thereby limiting the areal observation of intensity. But regardless of the availability of calibration events, as pointed out in an earlier section it is important that one first achieve consistency throughout a region, and then concentrate on removing bias by detailed empirical studies.

The nature of these studies can be briefly outlined. Select a network composed of more stations than were used in this report, perhaps 50, such that at least six or eight stable network subsets can be used. Unstable networks (as Network 4) should not be included. Increase the number of events to a far larger number than used here, perhaps 40. Critically read and re-read arrival times for all events at all stations. Using the constraints of network clustering, goodness-of-fit, anomalies from known explosions or "well located" earthquakes, reasonable functions (perhaps linear, but at least smoothly varying), and maximum permissible anomaly values, one could program and determine in a least-squares sense the best fit of all locations.

Aleutian regional anomalies

The derived anomaly functions shown in Figures 23a and 23b generally vary nearly continuously with longitude. This result may appear to be at variance with the conclusions drawn in previous reports (Chiburis 1968; Chiburis and Ahner, 1970), wherein station anomalies, determined from spatially separated explosions, were shown to be essentially constant, at least across an area approximately 70 km x 25 km. However, it must be pointed out that the functions derived in this report are made to change continuously for two reasons: (1) most of the events are farther apart than the distance over which the anomalies would normally be expected to be constant (probably about 100 km), such that a single anomaly could not be sensibly used as a correction; and (2) convenience. In spite of this, and also to provide a single value for a finite region, constant anomalies within regions of the Aleutian Islands can be determined from the values shown in Figures 23a and 23b by averaging several anomalies over areas somewhat larger than desirable. Because of the lack of events, the regions and the

constant anomalies are arbitrary, as the results of determining the step functions indicate in Figures 25a and 25b. The location results obtained by using these regional anomalies are summarized in Table XV, in which it can be seen that good clustering and low standard deviations are being achieved to about the same degree as in the Aleutian functional anomaly case. Interestingly enough, the only event for which Network 4 was not included in the results is Andreanof-11. This suggests that perhaps constant anomalies over fairly broad regions may provide more stability to networks with geometries like Network 4.

In an operational sense, the regional anomalies thus determined (Figures 25a and 25b) are the ones to apply when locating events in the Aleutian Islands with any combination of the 14 stations in this report.

Incidentally, additional stations can be added to this 14-station network by first locating one or (better) several events with those stations having anomalies. With the resultant epicenters, an (average) anomaly can then be computed for the station to be added. For subsequent events in that region, the original network and the new station (or subsets of them) can now be used for locating. In this "bootstrapping" way, any number of new stations can be incorporated into an existing network such that eventually all stations of any importance would be able to contribute equally and consistently to any solution.

Summarizing the results of fitting functions to the observed anomalies in various ways, we conclude that the set of constant regional functions derived are plausible and estimate the station anomalies for events in the Aleutians. The anomalies, when applied as corrections, are believed capable of providing more accurate relative locations for events between the Fox Islands and the Near Islands.

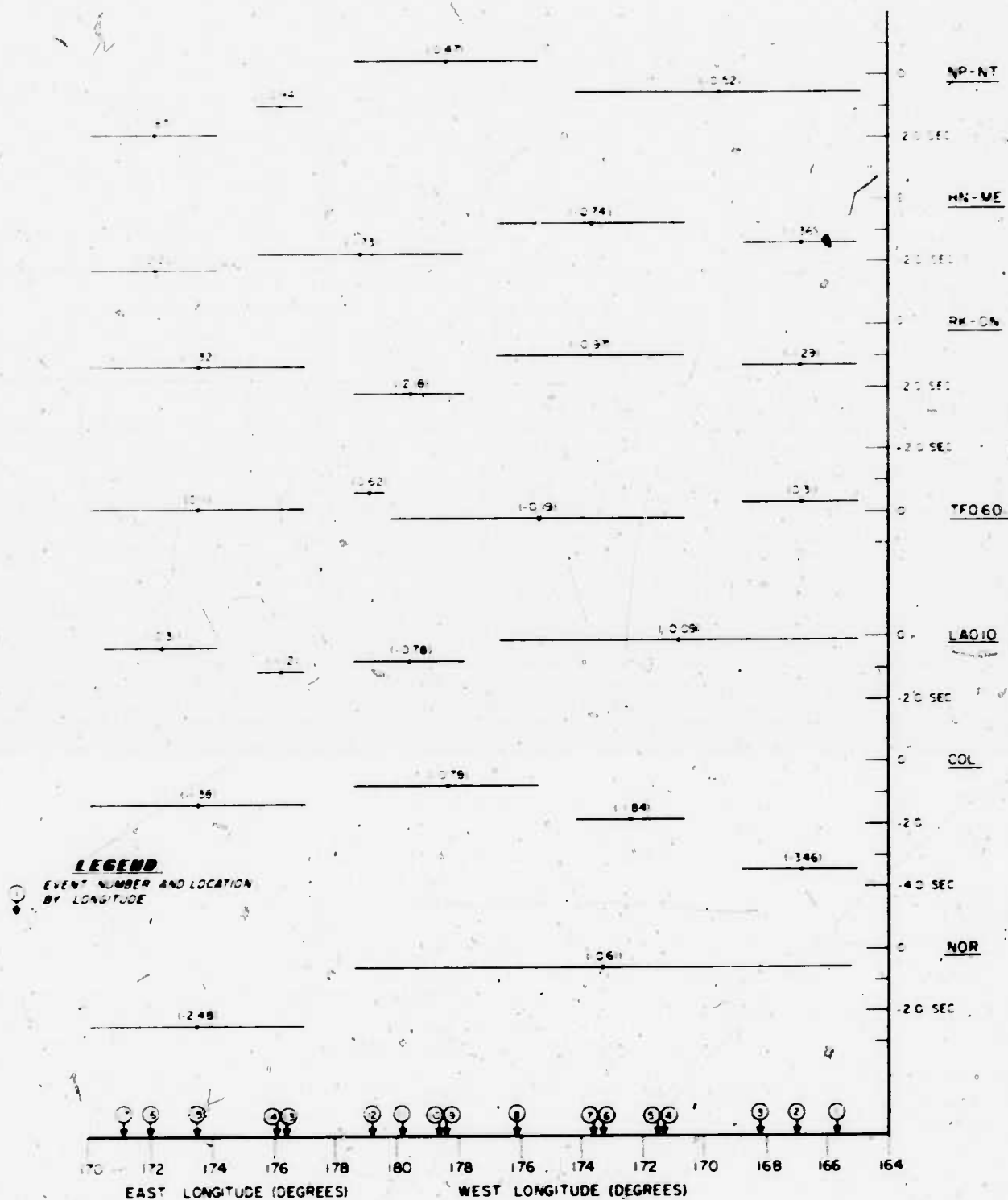


Figure 25a. Regional anomalies for Aleutian Islands events.

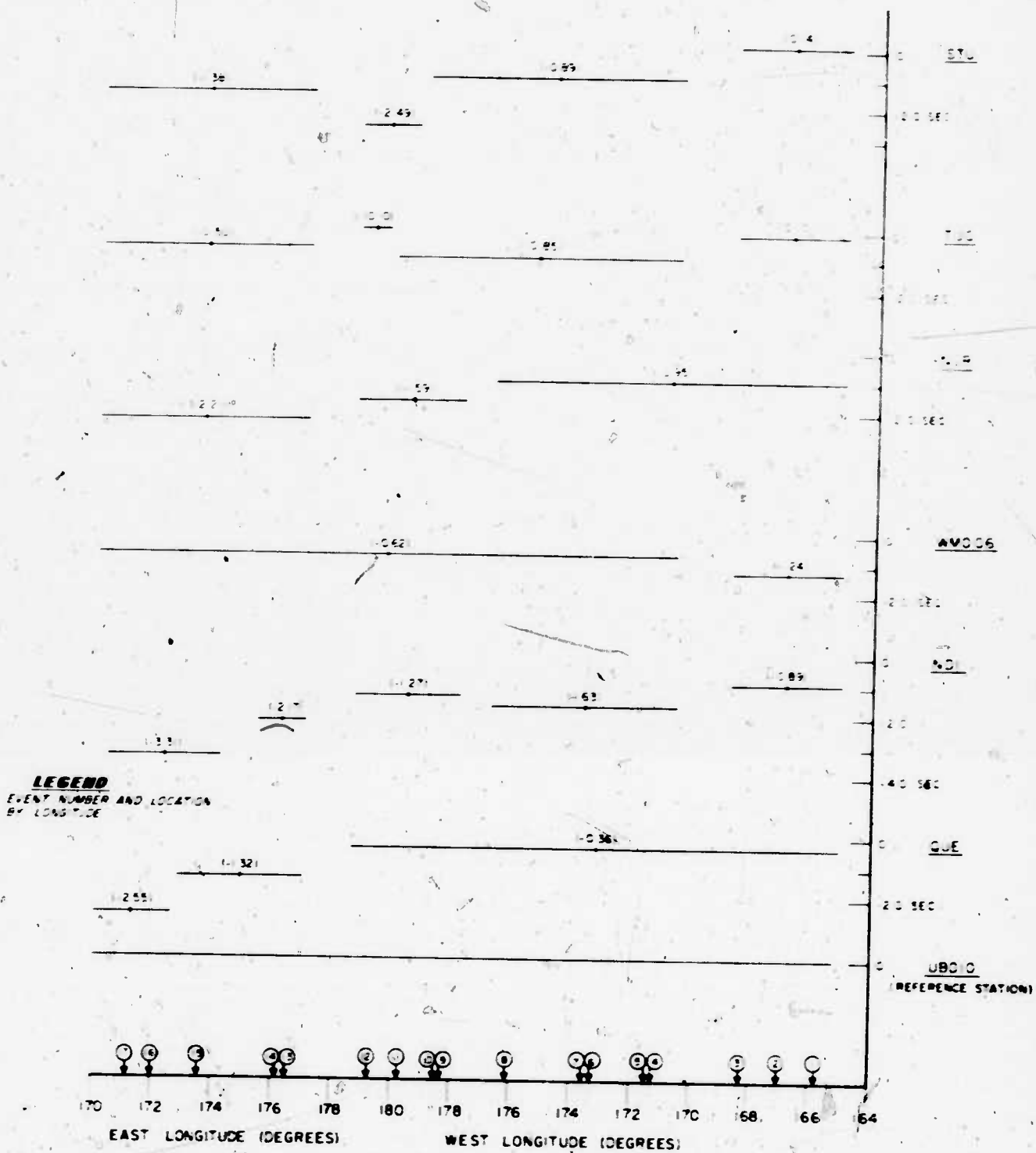


Figure 25b. Regional anomalies for Aleutian Islands events.

TABLE XV
LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY
APPLYING REGIONAL ANOMALIES

Network	Fox 1			Fox 2			Fox 3			Fox 4			Fox 5			And 6			And 7			And 8			And 9		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)
1	5.6	.130	3.6	6.0	.301	3.2	5.4	.283	0.8	3.2	.221	2.4	2.5	.147	2.4	2.1	.170	0.7	2.1	.222	1.6	1.6	.109	3.2	8.1	.101	2.4
2	5.2	.075	2.0	13.8	.312	10.4	1.9	.299	6.0	1.9	.136	3.2	4.2	.188	4.8	2.1	.093	0.4	2.0	.193	0.4	3.0	.193	6.4	5.0	.125	4.4
3	5.0	.144	3.2	2.8	.160	4.4	8.5	.211	3.2	6.0	.134	1.6	1.4	.179	1.6	7.0	.200	5.6	8.6	.214	2.8	7.6	.095	3.2	10.8	.245	1.2
4	4.2	.116	5.6	11.4	.139	13.2	6.5	.180	3.6	9.4	.171	7.6	6.5	.190	7.6	11.5	.158	8.0	7.2	.167	3.2	11.8	.217	8.8	14.1	.181	5.2
Mean	5.5	.116	3.6	8.5	.228	7.8	6.1	.243	5.4	5.1	.190	4.1	3.8	.226	4.1	5.8	.125	5.5	7.4	.195	2.0	7.0	.141	5.4	9.5	.188	3.5

Network	And 10			And 11			Nat 12			Nat 13			Nat 14			Nat 15			Nat 16			Year 17			Average of Shifts from Mean		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)	From Input (km)	From Mean (σ)	From Mean (km)
1	2.1	.107	1.2	15.1	.381	0.8	8.4	.195	1.6	10.7	.192	1.6	7.2	.159	2.0	20.0	.214	1.8	22.8	.212	2.4	13.5	.223	4.8	2.2		
2	6.8	.117	4.0	17.4	.408	6.4	3.4	.149	2.8	13.4	.115	4.8	6.3	.121	6.0	16.0	.121	8.0	24.4	.221	4.8	18.2	.204	9.6	2.3		
3	7.8	.181	6.4	17.4	.408	6.4	17.4	.408	6.4	8.0	.155	4.4	10.5	.080	3.2	17.0	.121	5.6	3.2	.089	0.4	5.2	.113	11.6	4.2		
4	7.1	.160	6.0	18.0	.442	4.4	9.6	.203	1.2	16.5	.269	6.4	9.5	.093	5.6	24.5	.220	6.8	26.2	.093	5.6	16.5	.146	1.2	8.1		
Mean	4.7	.166	3.9	17.0	.346	4.0	8.9	.179	2.2	12.2	.278	4.3	7.9	.113	4.2	22.0	.190	5.8	23.4	.154	3.5	13.5	.166	5.3	5.0		

*Not fit @ not used in forming mean

SYNTHETIC EARTH STUDIES

All the preceding results were obtained using real events and real arrival time data recorded by fourteen stations. These data necessarily contain time errors which are due to (1) reading precision because of less than perfect signal quality; (2) unaccountable travel-path effects (anomaly instability); and (3) station timing system errors. It would be desirable to completely eliminate the last two types of errors and to be able to concentrate on investigating particular aspects of the functional anomaly technique in order to verify or refute the general method. To achieve this, a data set was synthesized by assuming that the Herrin (1968) tables are perfect; from this ideal earth, theoretical arrival times were computed at the same fourteen stations for twelve hypothetical events equispaced across the Aleutians from the Fox to the Near Islands, but including the known LONG SHOT location in the Rat Islands. The latitudes and longitudes of the hypothetical events plus LONG SHOT are given in Table XVI. For simplicity, all events were assumed to have surface foci. The effect of ever-present reading error was incorporated in the following manner: a set of numbers was drawn randomly from a normal population (Huntsberger, 1961) by use of random number table. The set was then scaled to maintain a standard deviation of approximately 0.25 sec for each event, using all fourteen stations, by the relation

$$Y_i^j = (X_i^j - \bar{X}^j) [0.25(N-1)(S_X^j)^{-2}]$$

where Y_i^j is the random time error (attributable to reading) applied to the i th station for the j th event, X_i^j is the number drawn from the normal population, \bar{X}^j is the mean of the X_i^j 's

TABLE XVI
Event Parameters for 11 Hypothetical Epicenters Plus LONG SHOT

<u>Event</u>	<u>Latitude (Degrees)</u>	<u>Longitude (Degrees)</u>
Fox 1	53.50 N	166.00 W
Fox 2	53.00 N	168.00 W
Fox 3	52.40 N	170.00 W
And 4	52.00 N	172.00 W
And 5	51.60 N	174.00 W
And 6	51.50 N	176.00 W
And 7	51.50 N	178.00 W
Rat 8 (Long Shot)	51.44 N	179.18 E
Rat 9	51.40 N	178.00 E
Rat 10	51.60 N	176.00 E
Near 11	52.20 N	174.00 E
Near 12	52.80 N	172.00 E

for the j th event, N is the number of stations (14), and $(S_x^j)^2$ is the variance of the numbers drawn for the j th event. The entire set of random errors is given in Table XVII by station and by event. No random errors were applied to LONG SHOT, because when the anomalies (determined with real arrival times) are considered, random errors are already included.

The location errors produced solely by these reading errors are shown in Figure 26 for the same network subsets as defined in the previous sections of this report (Table V). The average location errors for each network are as follows:

<u>Network</u>	<u>Average Error, km</u>
1	4.1
2	5.7
3	5.4
4	7.2

These errors generally reflect a lower limit of accuracy expected for each network in locating events in the Aleutian Islands when reading errors are on the order of 0.25 sec.

Synthetic functional anomalies

Using the observed LONG SHOT anomalies as constraints, piecewise-linear synthetic functional anomalies were contrived for each station and are plotted in Figures 27a and 27b as functions of longitude. The only restrictions imposed on the synthetic functions were that they remain within reasonable anomaly ranges and that they contain no large discontinuities when viewed as a function of longitude.

If these anomalies, referred to as syn-1, are assumed to be caused by the synthetic earth, locations can be obtained using

TABLE XVII
SET OF RANDOM ERRORS APPLIED TO THEORETICAL ARRIVAL TIMES

Event	NP-NT	IN-ME	HK-ON	LAOLO	MMOOO	UBOLO	TILOO	IUC	COL	NOR	STU	NUR	QUJ	NDJ
Fox 1	.277	.089	.324	.168	.376	-.157	-.028	.081	-.320	-.241	-.439	.201	-.294	-.027
Fox 2	.046	-.004	.059	.064	.078	-.220	.173	-.211	-.542	.378	.182	-.300	-.110	.406
Fox 3	-.226	-.004	.000	.297	.125	.526	-.487	.057	-.330	.214	-.052	-.190	.093	-.022
AND 4	.172	-.164	-.422	.326	-.105	-.091	.258	-.313	-.088	.098	-.178	-.122	.529	.090
AND 5	.423	-.222	-.127	-.335	-.177	-.508	.353	.192	-.069	.088	.058	.059	.212	.053
AND 6	-.340	.342	.279	.125	-.013	-.048	-.022	.184	.247	.277	-.226	-.530	-.189	-.086
AND 7	.057	.264	-.220	.096	.450	-.130	.128	-.278	.275	.203	-.021	-.084	-.363	-.419
Long Shot	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Rat 9	-.107	.140	-.085	.202	.058	.028	-.178	-.188	.275	.064	-.207	-.500	-.088	.587
Rat 10	-.334	.221	.002	.289	-.151	-.261	.447	.178	-.008	-.308	-.238	.084	-.231	.311
Near 11	-.527	.142	-.142	.169	-.212	.148	-.124	.403	-.343	-.033	.375	.132	-.051	.065
Near 12	-.127	-.189	-.417	.059	.298	.077	.292	.336	-.032	-.146	-.433	.277	.185	-.178

FOX 1

AND 7

FOX 2

RAT 8
LONG SHOT

FOX 3

RAT 9

AND 4

RAT 10

AND 5

BEAN 11

AND 6

BEAN 12

LEGEND

- HYPOTHETICAL EVENT
- DISTANCE LOCATION
- LOCATION SHIFT USING NETWORK NUMBER 1

Figure 26. Location shifts of hypothetical events due to applied random errors ($\sigma = 0.25$ sec).

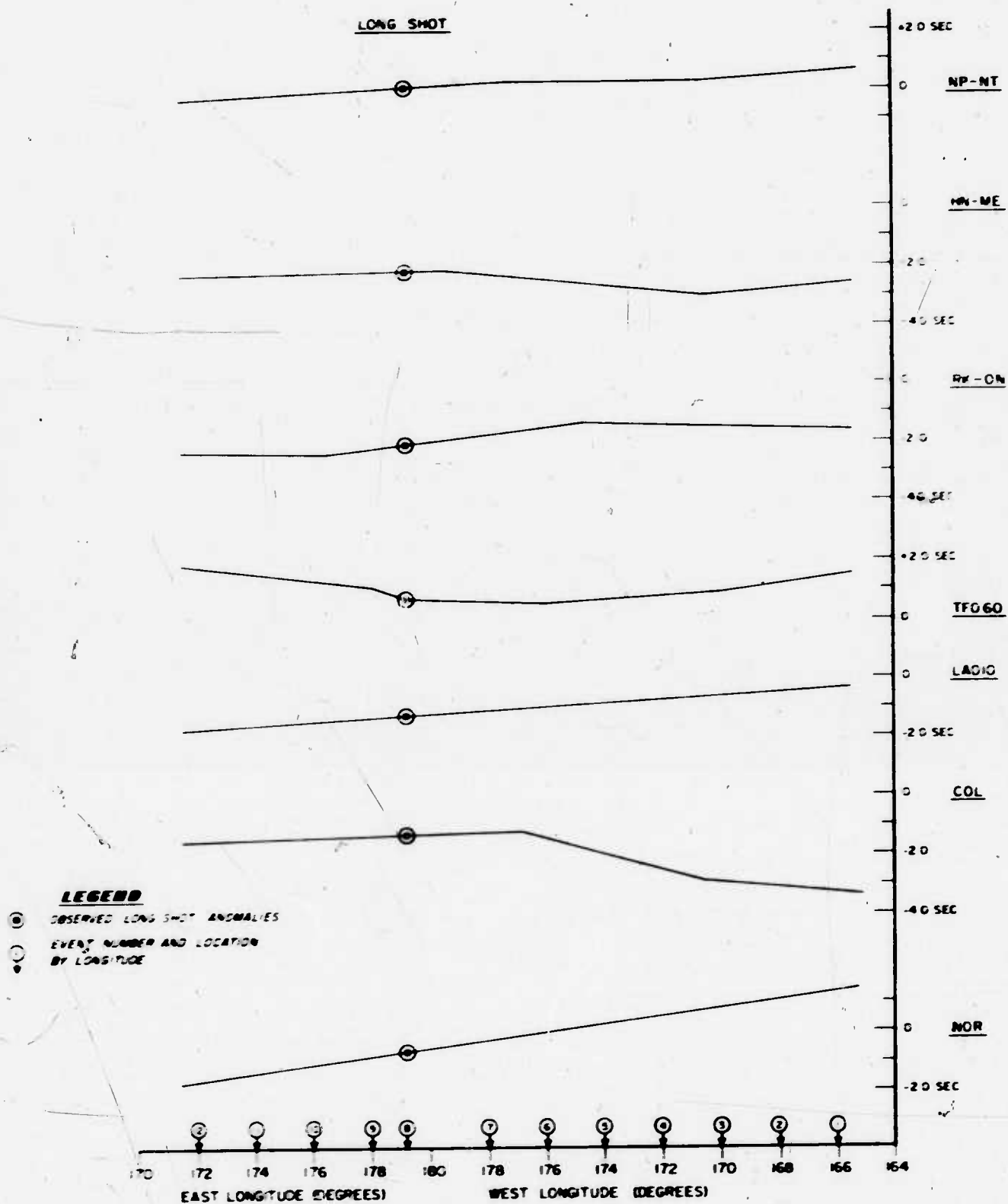


Figure 27a. Contrived functional anomalies (Syn-1) using synthetic data.

the four networks with no corrections applied. Symbolically, the arrival time T at station i for each event is made up of the following:

$$T_i = H_i + (A_i)_{\text{syn-1}} + E_i$$

where H is the theoretical time from the hypothetical epicenter, $A_{\text{syn-1}}$ is the contrived anomaly applicable to that event, and E is the random error previously discussed ($\sigma(E_i) = 0.25$ sec for the set of fourteen stations). The location results are shown in Figure 28. The average and range of location errors for the four networks and for the twelve events are summarized in Table XVIII.

These errors are absolute because the true locations are known. The wide range of errors for a particular network clearly shows the difficulty one can have in attempting to understand the anomaly effect across a region as large as the Aleutian Islands, especially when real events are mislocated and are at different depths. Network 3 appears to exhibit the most instability, although it has a geometry similar to that of Network 2. The reason is that the stations in Network 3 have the most erratic and largest functional anomalies.

The contrived anomalies and the anomaly variations for the stations used are not considered too extreme or unrealistic. Similar and even larger variations have been observed in the station anomalies computed from the following explosion regions: the Nevada Test Site in southern and central Nevada, the SHOAL event in western Nevada, the RULISON event in northwestern Colorado, the GASBUGGY event in northwestern New Mexico, and the GNOME event in southeastern New Mexico (Chiburis and Ahner, 1970). The range of anomalies computed from these explosions at some stations exceeds 5 sec, with 2-3 sec being common. Significantly, the

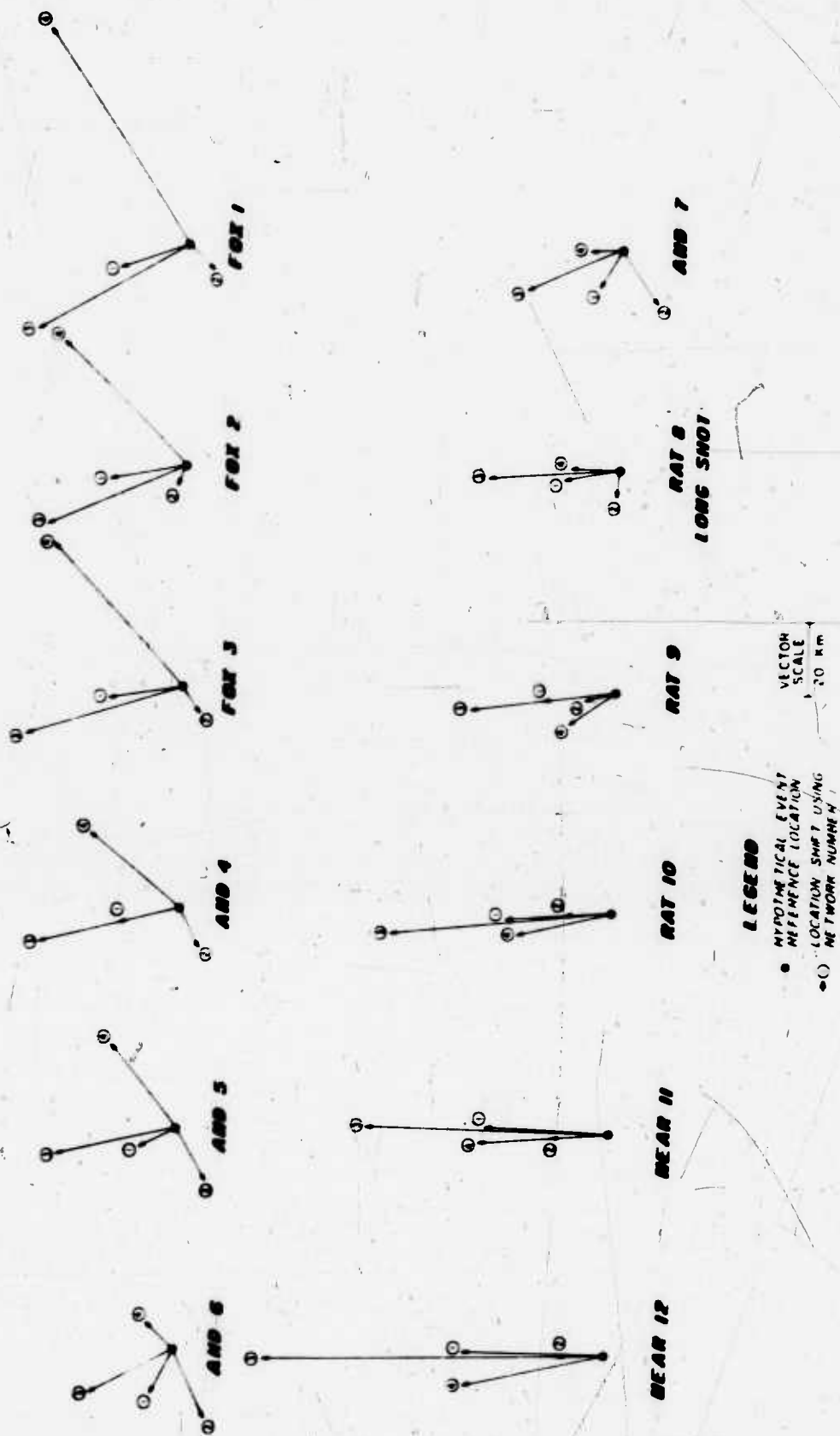


Figure 28. Location shifts using theoretical arrival times with random errors and Syn-1 anomalies as earth-model errors.

TABLE XVIII
Location Results with Synthetic Earth Model

<u>Network</u>	<u>Average Error, km</u>	<u>Error Range, km</u>
1	22.1	12.5 - 39.9
2	12.5	6.2 - 21.0
3	47.7	26.2 - 95.1
4	32.6	9.3 - 71.2

distance between SHOAL and GASBUGGY is about 1600 km, which is of the same order as the distance between the Fox Islands and Near Islands.

The results as shown in Figure 28 and Table XVIII were obtained with four subsets of a fourteen station network. If more stations were available and other more stable network subsets taken, the location of any particular event in the Aleutians would still be meaningless, except in a general way (see the earlier section of this report on LONG SHOT using subsets of a 329-station network). The point is that if no information is available on travel-time anomalies from a region of interest, then depending on the particular network selected for locating (even assuming the network is reasonably stable), the true location errors may be anywhere from zero to 50 km or more. It can be further pointed out that in some regions the anomalies may be distributed such that the resultant errors would be larger.

Referring again to Figure 28, the results using the four networks for each event are quite variable, but for any one network the shift vectors from event to event are considerably more consistent; although the errors are large, they vary slowly and regularly across the region. For example, using Network 1, Fox-1 shifts about 21 km north-northwest from the true location, and LONG SHOT shifts about 16 km, but also to the north-northwest. Therefore, Fox-1 relative to LONG SHOT is 6 km in error, etc. Table XIX gives the absolute and relative (to LONG SHOT) errors for all events located by Network 1. On the average, the relative errors are reduced by a factor of two over the absolute errors. For Network 3, which happens to have the poorest distribution of anomalies (as evidenced by the high average absolute error), the same comparison relative (to LONG SHOT) yields the results given in Table XX.

TABLE XIX

Absolute and Relative (to LONG SHOT) Location Errors for
Hypothetical Events Using Network 1 and Synthetic Earth-Model

<u>Event</u>	<u>Absolute Location Error, km</u>	<u>Relative Location Error, km</u>
Fox-1	20.8	5.3
Fox-2	21.9	6.2
Fox-3	21.1	5.6
And-4	18.3	2.6
And-5	14.1	4.0
And-6	13.8	12.9
And-7	12.3	11.7
LONG SHOT	15.7	--
Rat-9	22.6	8.3
Rat-10	30.7	15.4
Near-11	33.6	18.6
Near-12	<u>39.9</u>	<u>24.9</u>
Average	22.1	10.5

TABLE XX

Absolute and Relative (to LONG SHOT) Location Errors for
Hypothetical Events Using Network 3 and Synthetic Earth-Model

<u>Event</u>	<u>Absolute Location Error, km</u>	<u>Relative Location Error, km</u>
Fox-1	48.3	21.5
Fox-2	42.1	13.6
Fox-3	45.6	12.2
And-4	40.2	7.2
And-5	34.3	6.1
And-6	26.2	16.6
And-7	29.1	13.5
LONG SHOT	36.9	-
Rat-9	44.3	8.2
Rat-10	62.8	25.8
Near-11	67.4	30.5
Near-12	<u>95.1</u>	<u>58.1</u>
Average	47.7	19.4

Therefore although each network yields very different locations for an event (due to different distributions of the station anomalies within that network), the average location errors of the set of events relative to a calibration event are reduced by a factor of at least two when a constant network is used. This result further substantiates the conclusions drawn in a previous report (Chiburis and Ahner, 1970) in which the relative location accuracy of 2-3 km for a fairly small region was shown to be unaffected by travel-time anomalies if and only if a constant network was used for locating a set of events. However, for the synthetic data set used here, and for the real Aleutian Islands data set in general, it is known that the station anomalies across such a large region are not constant; thus the relative accuracy for any network is expected to be lower than that possible for the location of events within a small region across which the anomalies are constant.

Equally important as the criterion of constant anomalies, however, is that of "network effect". Any seismic network is uniquely defined by the stations in it and their geometrical relationships to the particular epicentral region of interest. These relationships are functions of epicentral distance Δ and azimuth θ , and of the travel-time table, $H(\Delta)$, neglecting depth of focus. Specifically, for the i th station,

$$\frac{\partial H_i(\Delta)}{\partial \Delta_i} \begin{pmatrix} \sin \theta_i \\ \cos \theta_i \end{pmatrix}$$

are the slopes of the travel-time/distance curve modified by the sine or cosine of the azimuth depending respectively on whether the rates of change with longitude or latitude are

desired. If the region under investigation is large enough, these slopes of the travel-time curve change significantly at a station such that the advantages of constant network and constant anomalies are considerably undermined. This fact may be demonstrated with the synthetic data by allowing the known LONG SHOT anomalies to be the only time errors across the entire Aleutian Islands region. In this case, the arrival time data are constructed as

$$T_i = H_i + (A_i)_{LS}$$

where $(A)_{LS}$ is the LONG SHOT anomaly and the other terms being defined as before. This means that if the LONG SHOT anomalies are applied as corrections to the arrival time data, all location errors obtained with any network, constant or otherwise, would be zero. If, on the other hand, constant networks are used but no anomalies are applied, the results are as shown in Figure 29. Here it can be seen that Networks 1 and 2 have only slight network effects on relative location accuracy due to slope perturbations. Network 3, however, has a strong network effect in that the errors have similar directions, but the magnitudes differ by a factor of almost 3 between the Fox and Near Islands. The effect on Network 4 produces errors which change direction by about 60° and magnitude by a factor of $2/3$ between the Fox and Near Island. These shift differences are due to network geometry, to the network relationship to the Aleutian Islands region, and to the non-linearity of the travel-time curves, because the network itself and the station anomalies are held constant; the only parameters which are variable are the station distances and azimuths to the twelve events. If constant anomalies were the only criterion necessary to maintain relative accuracy over a broad region, the location shifts for a constant network would all have had the same magnitude and direction. This is true over a small portion of the Aleutian

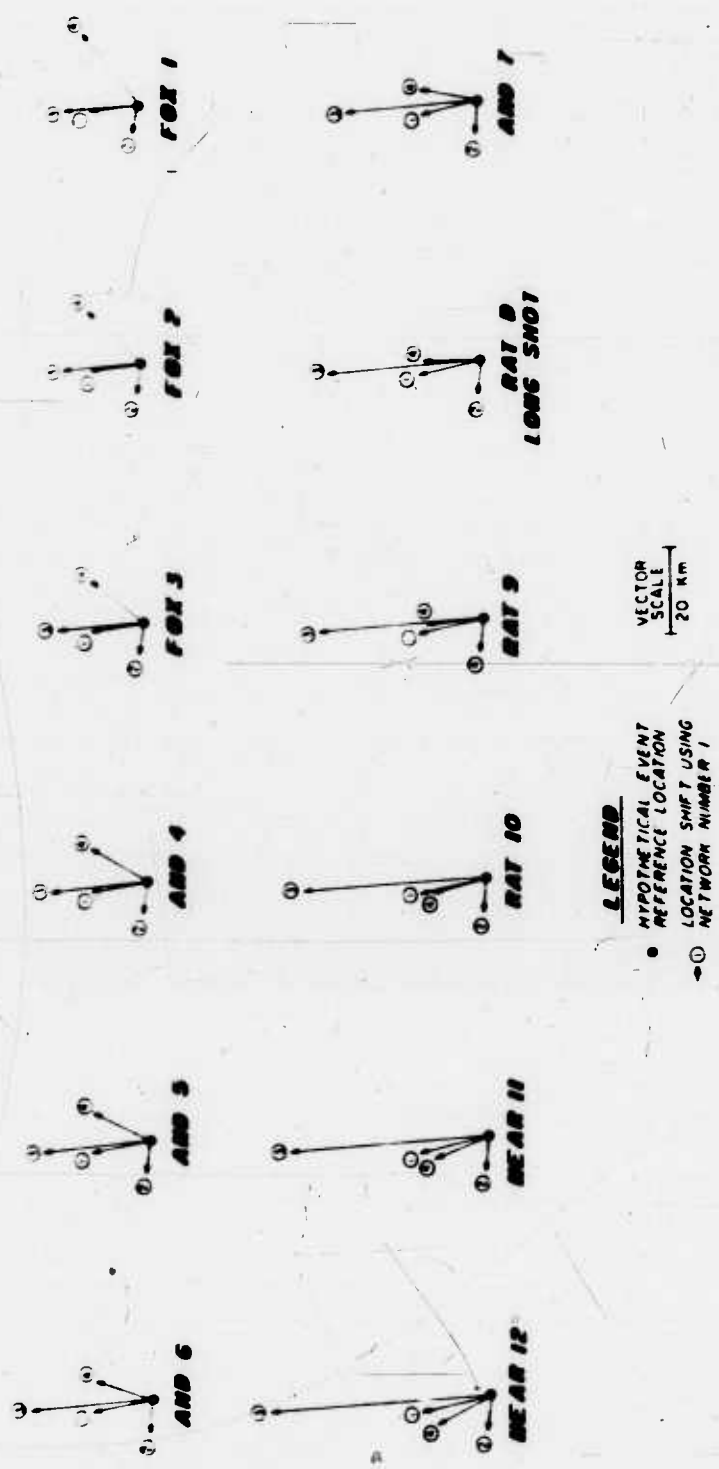


Figure 29. Location shifts using theoretical arrival times with LONG SHOT anomalies as earth-model errors.

region, in which the location shifts are nearly identical, but it is not true in general from one end to the other. For example, using Network 3, And-7 and Rat-9 relative to event 8, which is LONG SHOT, have errors of 4 km and 3 km respectively, whereas events Fox-1 and Near-12 relative to event 8 have errors of 20 and 16 km respectively. The latter errors are far larger than the 3-5 km errors expected if the region is small enough that the travel-time/distance slopes do not significantly change.

Therefore if a constant network is used, even if the anomalies are constant throughout a large region but are not applied, relative accuracy diminishes as a function of travel-time slopes with increasing distance between events due strictly to the network effect. Of course if the anomalies are applied as corrections, there would be no location errors except those due to reading precision. However, as was shown in Figure 28 and Table XIX and XX, using data which include the synthetic functional anomalies, one can achieve at least some improvement in relative accuracy. This is possible because the contrived anomalies are producing an effect greater than that produced by network geometry.

When the synthetic functional (syn-1) anomalies are included in the time data, if it is erroneously assumed that the LONG SHOT anomalies are valid across the entire Aleutians Islands region, they can be applied as corrections to the arrival times, and locations can be made with the four networks. The arrival time data now are

$$T_i = H_i + (A_i)_{\text{syn-1}} + E_i - (A_i)_{\text{LS}}$$

(the process of computing locations with this relation can also be graphically obtained by simply subtracting vectorially the

shifts shown in Figure 29 (LONG SHOT anomalies) from the shifts in Figure 28 (syn-1 anomalies) for each event and for each network. For Fox-1 and for Network 4, this vector process is shown in Figure 30). The average location results for each network are given in Table XXI, which also includes for comparison the averages already given in Table XVIII obtained when no anomalies were applied.

For all networks, the average errors are reduced, and except for Network 2, which has a low average to begin with, the reductions are significant. These results suggest that, although the LONG SHOT anomalies are not completely valid across the entire region, they are at least partially effective in removing some of the gross bias errors. Stated differently, the effect of the LONG SHOT anomalies is greater than the effect of the synthetic anomaly variations; when the LONG SHOT anomalies are applied as corrections, first-order bias effects are eliminated but second-order bias effects remain. These second-order errors remain even for those events adjacent to LONG SHOT (And-6, And-7, Rat-9, and Rat-10), where the anomalies would be expected to be approximately valid, since the synthetic anomalies were made to change only slowly as a function of distance away from LONG SHOT. Figure 31 shows the results of applying the LONG SHOT anomalies to the synthetic data and locating with the four networks. Table XXII summarizes the complete results. The errors in the mean location (small circles on the Figure) are less than 10 km for events 4 through 9; for events 6 through 11 the clustering errors are reduced to less than 6 km and the standard deviations are acceptably low. The errors in the mean location indicate absolute accuracy, while clustering errors indicate relative accuracy. Therefore, as noted earlier, clustering and low standard deviation, alone or together, are necessary but not significant to guarantee improved absolute accuracy.

TABLE XXI

Average Location Errors Using LONG SHOT Anomalies
with Synthetic Earth-Model

<u>Network</u>	<u>Average Error km, Using LS Anomalies</u>	<u>Error Range, km</u>	<u>Previous Average Error, km, Using no Anomalies</u>
1	11.4	3.7 - 23.8	22.1
2	10.6	1.4 - 16.9	12.5
3	20.0	9.7 - 42.8	47.7
4	21.4	5.2 - 49.1	32.6

TABLE XXII

Average Location Shifts of Mean Epicenter, Standard Deviations (σ), and Clustering Effect Using LONG SHOT Anomalies with Synthetic Earth-Model

<u>Event</u>	<u>Error in Mean Location</u>	<u>Average Shift From Mean</u>	<u>Mean σ</u>
Fox 1	12.7	25.3	0.85
Fox 2	13.0	13.9	0.87
Fox 3	13.1	18.0	0.81
And 4	6.8	10.7	0.64
And 5	1.0	10.2	0.54
And 6	10.0	5.7	0.39
And 7	9.7	3.5	0.17
Long Shot	----	----	----
Rat 9	5.0	5.5	0.26
Rat 10	15.0	4.5	0.31
Near 11	19.3	3.6	0.26
Near 12	26.2	10.4	0.59
Average		10.1	



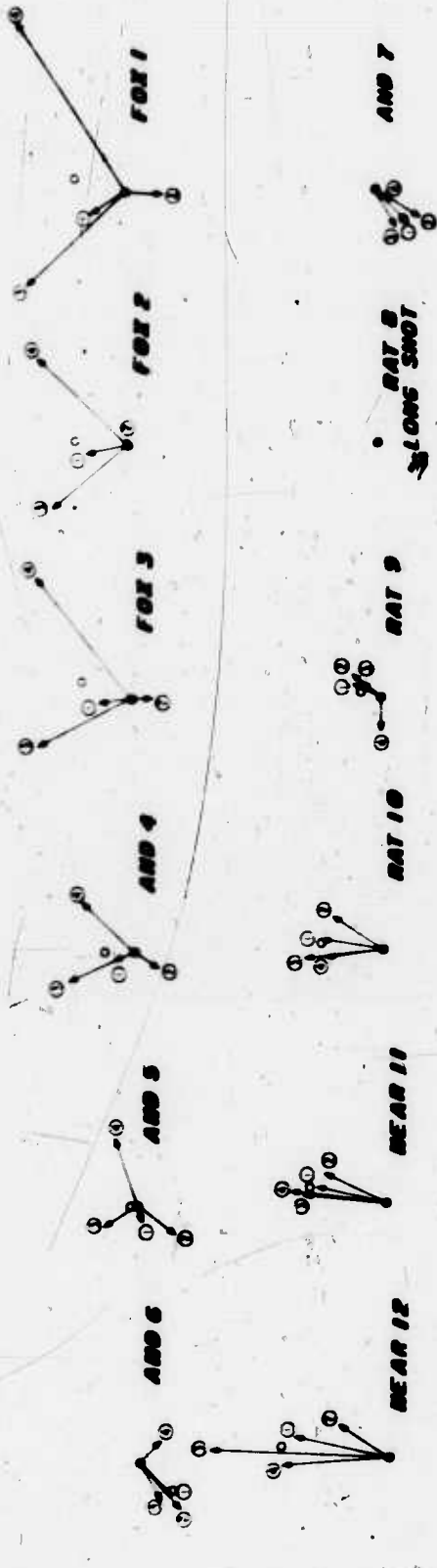
LEGEND

- NETWORK & LOCATION SHIFTS
- (1) FOX 1 REFERENCE LOCATION
- (2) SYN-1 ANOMALIES
- (3) RANDOM ERRORS
- (4) LONG SHOT ANOMALIES AS CORRECTIONS

VECTOR
SCALE

20 Km

Figure 30. Vector addition for resultant location shift.



LEGEND

- HYPOTHETICAL EVENT REFERENCE LOCATION
- MEAN LOCATION OF 4 NETWORK SOLUTIONS
- LOCATION SHIFT USING NETWORK NUMBER 1

VECTOR
SCALE
20 km

Figure 31. Location shifts using theoretical arrival times with random errors and Syn-1 anomalies as earth-model errors plus LONG SHOT anomalies as corrections.

Furthermore, the LONG SHOT anomalies appear to be valid only for the events immediately adjacent to it (events 7 and 9 at distances of about 180 km and 80 km respectively from LONG SHOT). The mean location error of event 7 is about 10 km; that of event 9 about 5 km. This result is in general agreement with previous conclusions concerning the size of an area across which a constant anomaly is good enough for accurate location (Chiburis and Ahner, 1970).

Anomaly interpolation using synthetic data

The location of LONG SHOT is known. If some location is assumed for event 1 (Fox Islands) and for event 12 (Near Islands), and if the anomalies are computed from the three locations with linear functions drawn between them, can improvement be gained in accuracy and in standard deviation over that obtainable if no anomalies are applied to the intervening events? Restated, can one combine the anomalies from a true location and from wrong locations and still expect to improve location capability? In the following discussion we will answer these questions in the affirmative.

Using the synthetic earth in which the anomalies are known, Fox-1 is deliberately mislocated by 0.2° north and Near-12 by 0.1° south. Computing the anomalies from these two fiducial locations and from the known LONG SHOT location, bilinear functions are fitted to the three constraints, as are shown in Figures 32a and 32b. Compare these functions with the synthetic functions originally contrived (Figure 27a and 27b).

Locating the twelve hypothetical events with the four network subsets and the bilinear functions (random reading errors are also included), gives the results shown in Figure 33. Because events 1 and 12 were deliberately given a location bias of 0.2° N

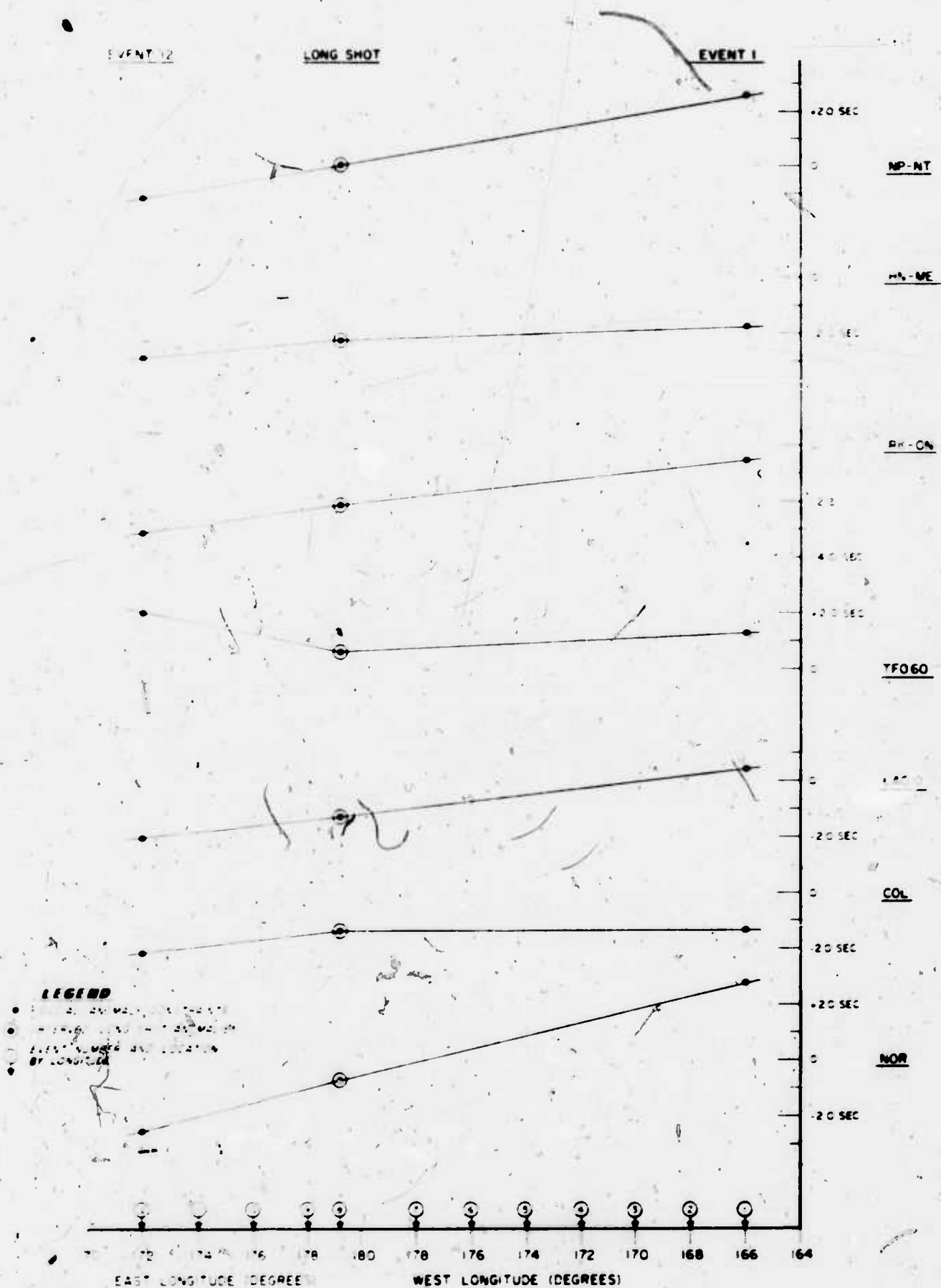


Figure 32a. Linear functional anomalies determined from two deliberately mislocated events plus LONG SHOT.

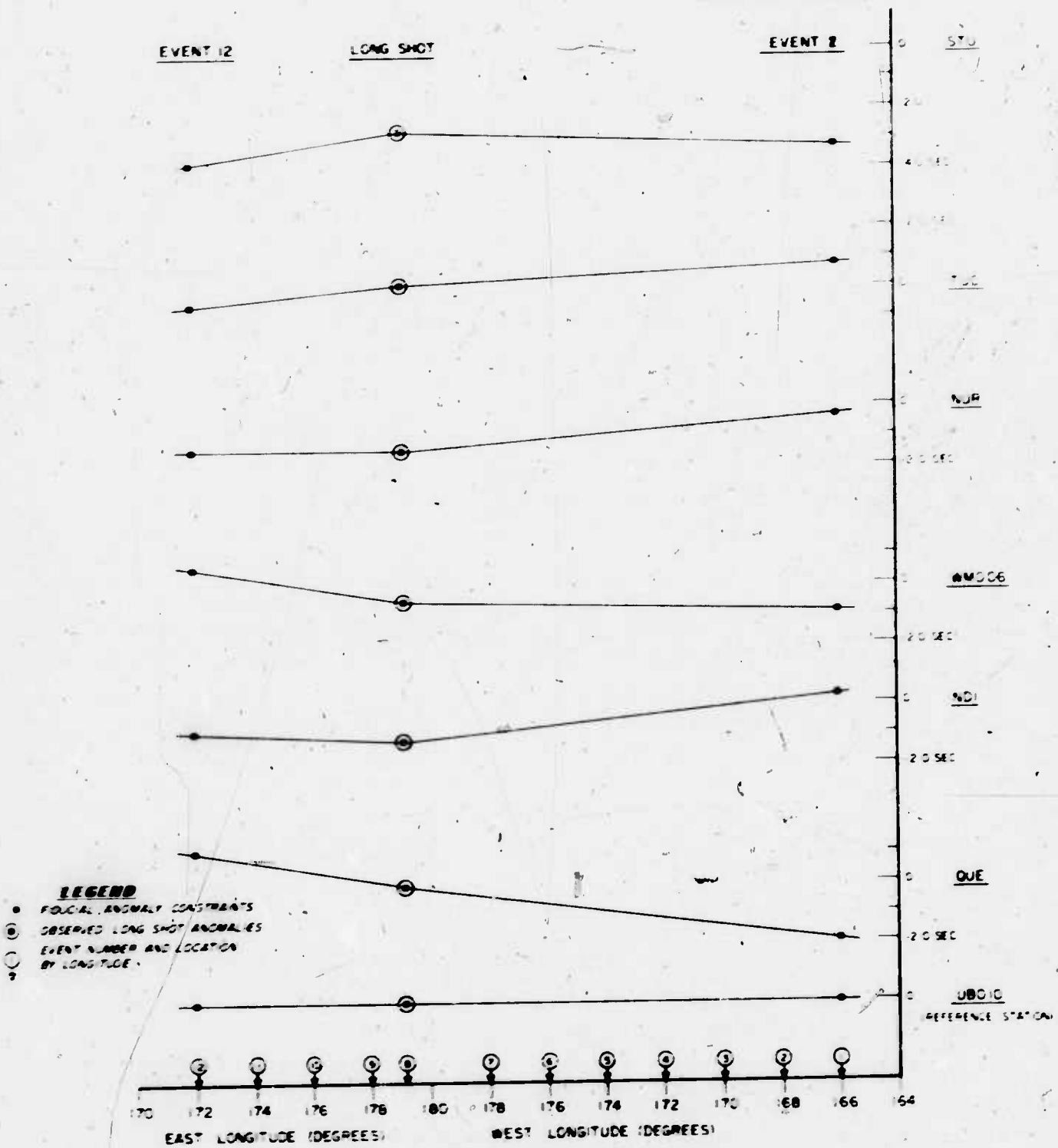


Figure 32b. Linear functional anomalies determined from two deliberately mislocated events plus LONG SHOT.

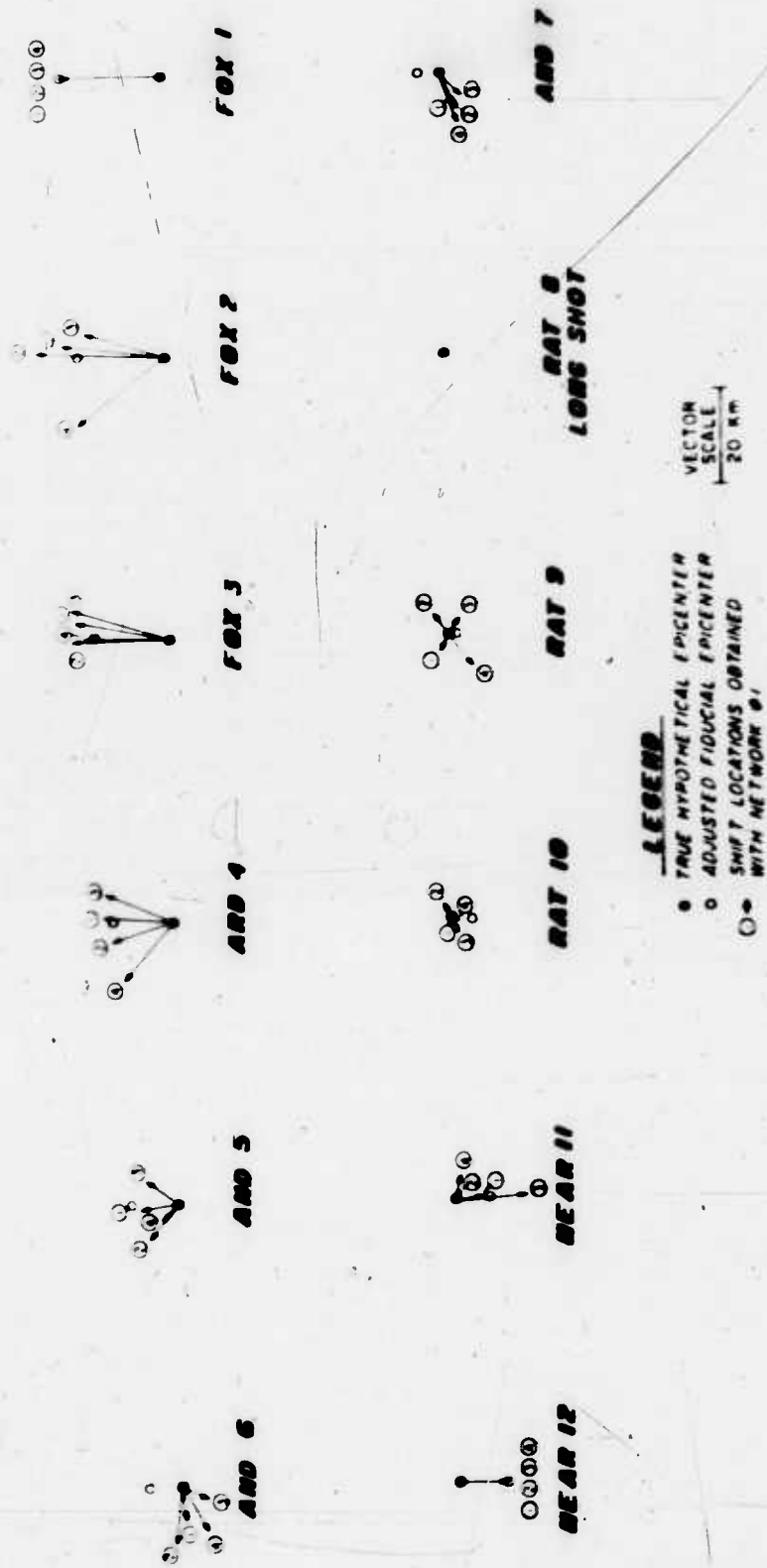


Figure 33. Comparison of least-squares solution errors with contrived functional anomalies at three stations.

and 0.1°S respectively, in order to discuss accuracies across the region, the other events need to be adjusted by an amount proportional to their locations relative to the calibration events. The adjustment relation is shown in Figure 34. The adjusted fiducial epicenters are shown as circles in the previous Figure 33.

The location errors relative to the adjusted epicenters and standard deviations are given in Table XXIII. Compared to the no-anomaly results with the same synthetic data (Table XVIII), significant improvement is obtained in relative accuracy by assuming the locations of "unknown" events and tying the anomalies to those of known explosions. The reason that the events And-6 and And-7 do not locate well is due to the nature of synthetic functions derived; many of the piecewise-linear functions were made to change sharply between events 5 and 8, which results in poor estimates of the anomaly when assuming strict linearity between the calibration events. Therefore, across a region the size of the Aleutian Islands, the technique of anomaly interpolation is valid and will yield improved relative locations. This conclusion bears directly on the interpolation results obtained with real data; viz, when several events are assumed to be located correctly and linear anomalies are fitted between them, the results are consistent both from clustering and standard deviation considerations (Figure 24 and Table XIII).

Step-off technique

A brief discussion is now given of a method, referred to as the "step-off" technique, that attempts to increase the area over which the known LONG SHOT anomalies remain valid. The observations which suggested the possible applicability of this technique were that the distribution of zero-mean time errors resulting

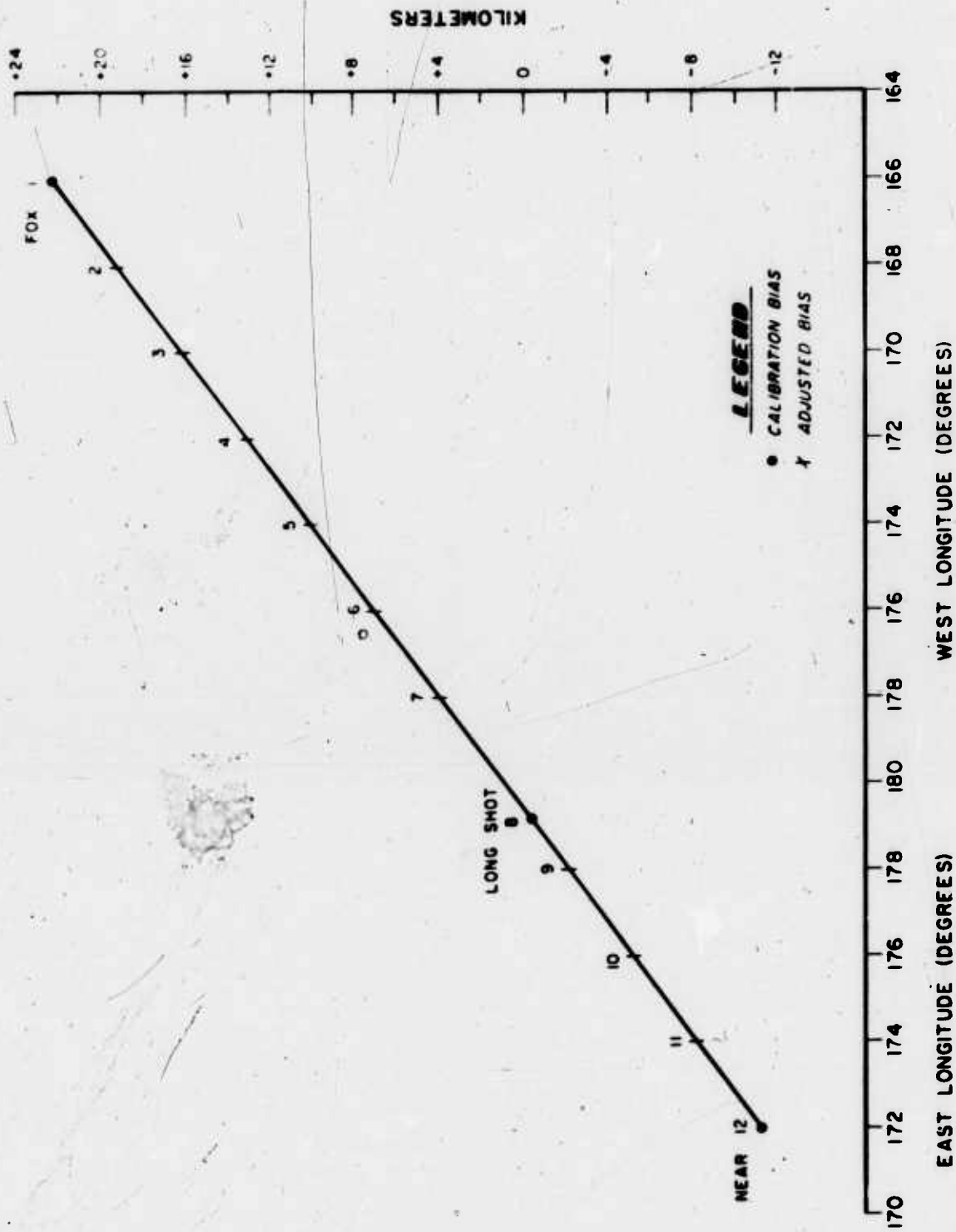


Figure 34. Location shifts obtained by applying functional anomalies shown in Figure 33.

TABLE XXIII
ADJUSTED LOCATION SHIFTS RELATIVE TO DELIBERATELY MISLOCATED CALIBRATION EVENTS

Network	Fox 1			Fox 2			Fox 3			And 4			And 5			And 6		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)
1	22.3	00	00	22.9	.372	4.4	20.9	.312	4.8	15.7	.339	2.4	8.5	.415	2.4	7.6	.318	11.2
2	22.2	00	00	28.4	.305	9.6	18.3	.325	2.4	14.2	.230	4.8	10.1	.398	8.4	12.4	.400	14.0
3	22.5	00	00	18.5	.202	4.8	22.1	.284	8.0	16.1	.333	6.4	8.7	.270	6.0	6.2	.076	13.6
4	22.5	00	00	24.0	.365	14.4	21.5	.181	5.0	16.7	.226	12.8	5.1	.274	7.2	11.2	.191	16.8
Mean	22.3	00	00	23.4	.341	8.3	20.7	.276	5.2	15.7	.282	6.6	8.1	.339	6.0	9.4	.221	13.9

Network	And 7			Nat 8			Nat 9			Nat 10			Near 11			Near 12		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)	From Input (km)	From Mean (m)	(km)
1	7.5	.207	10.4	00	00	00	3.7	.291	4.8	0.4	.242	5.6	6.9	.352	0.8	12.1	00	00
2	8.0	.168	10.8	00	00	00	5.5	.294	7.2	4.4	.119	8.0	1.6	.144	6.8	11.1	00	00
3	7.2	.153	11.2	00	00	00	4.0	.237	5.6	3.1	.248	4.4	16.4	.445	8.8	11.1	00	00
4	11.2	.203	14.0	00	00	00	8.6	.112	8.0	0.7	.299	4.0	5.4	.288	8.0	11.1	00	00
Mean	8.5	.183	11.6	00	00	00	5.4	.236	5.9	2.2	.227	5.5	7.6	.307	6.1	11.1	00	00

Average of Shifts
from Mean to Adjusted Shifts
(km)

5.2
8.0
7.4
10.1
7.7

from the least-squares solution followed fairly closely the distribution of functional anomalies contrived for the Aleutian Islands region. For example, using Network 1 and the synthetic data, the set of 12 hypothetical epicenters was located using only the LONG SHOT anomalies as corrections across the whole region; the residuals for stations HN-ME, STU, and TFO resulting from the least squares solutions, and the anomalies originally contrived for these stations are plotted as functions of longitude in Figure 35. As can be seen in the Figure, these residuals estimate quite well the anomalies actually incorporated into the arrival time data, especially in the vicinity of LONG SHOT. At larger distances, the residuals begin to diverge from the contrived anomalies as expected. Therefore, if one applies the LONG SHOT anomalies to an adjacent event (say event A) and then attributes the cause of the residuals resulting from the location of event A to a real change in the anomaly between the two events, these errors can be algebraically added to the LONG SHOT anomalies, and the sum applied as an anomaly correction to the next event (say event B). In this way, one can "step-off" away from LONG SHOT, event by event, and hopefully improve the bias normally observed between the Fox and Near Islands. The i 'th station's anomaly to be applied to the first event in distance away from LONG SHOT is just the LONG SHOT anomaly:

$$A_i^{(A)} = (A_i)_{LS}$$

These anomalies yield a location of event A with a set of least-squares errors $E_i^{(A)}$. The step-off anomaly to be applied to the second event away from LONG SHOT is

$$A_i^{(B)} = (A_i)_{LS} + E_i^{(A)}$$

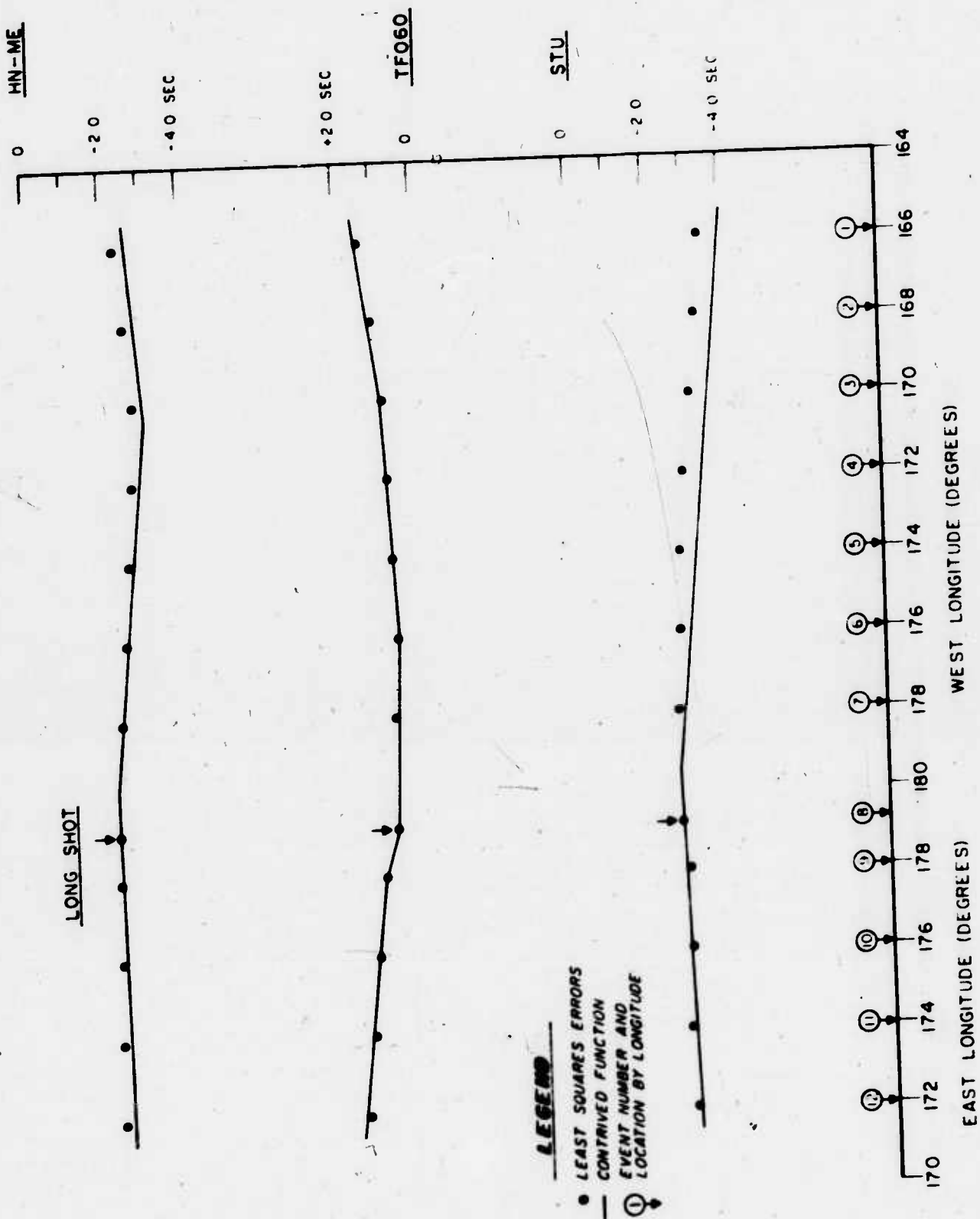


Figure 35. Bias adjustment relation for determining location errors shown in Figure 34.

yielding a new set of errors $E_i^{(B)}$. In general,

$$A_i^{(j)} = (A_i)_{LS} + E_i^{(j-1)}$$

Although the application of the step-off anomalies results in a considerably reduced standard deviation in the solutions, all of the final locations were found to be nearly identical (within 1/2 km) to those obtained by applying only the LONG SHOT anomalies. In other words, applying a set of residuals, which results from the location of one event, to the set of arrival times of an adjacent event has a negligible effect on the location, even though these applied errors are large. Table XXIV gives the least-squares errors from the final locations obtained by using the LONG SHOT anomalies; the three standard deviations, σ_0 , σ_{LS} , σ_{LS+E} , are respectively those obtained with no anomaly corrections, those with the LONG SHOT anomalies, and those with the LONG SHOT anomalies plus the least-squares errors from the adjacent event. The least-squares errors in locating event 7 (Andreanof) with the LONG SHOT (event 8) anomalies are given in the first column of Table XXIV. This set has a standard deviation of 0.201 sec. (The standard deviation obtained by applying no anomalies is shown as σ_0 .) Adding these errors to the LONG SHOT anomalies and locating event 6 results in a standard deviation of 0.408 sec instead of 0.478 sec as obtained with the LONG SHOT anomalies alone. When locating event 1 (Fox) using only the LONG SHOT anomalies, the standard deviation is 1.286 sec; if the least-squares errors from event 2 are stepped-off, the standard deviation is reduced to 0.414 sec. For the synthetic data set, the standard deviation when the LONG SHOT anomalies are applied, σ_{LS} , compared to the standard deviation without anomalies, σ_0 , is

TABLE XXIV
Set of Least-Squares Errors Applied in Step-Off
Technique and Resultant Standard Deviations. (See Text)

<u>Station</u>	LEAST-SQUARES ERRORS (IN SECONDS)						
	<u>AND7</u>	<u>AND6</u>	<u>AND5</u>	<u>AND4</u>	<u>FOX3</u>	<u>FOX2</u>	<u>FOX1</u>
COL	-.23	-.54	-.84	-1.01	-1.58	-1.51	-1.81
NP-NT	-.10	.22	.64	.63	.75	.64	1.25
NOR	.47	.90	1.12	1.61	2.31	2.46	2.33
LA010	.11	.18	.08	.89	.81	1.08	.98
UB010	-.27	-.28	-.61	-.23	-.38	.24	-.56
RK-ON	-.13	.54	.53	.25	.74	.55	.72
TFO60	.02	-.32	.25	.17	.14	-.39	.30
TUC	.19	.76	1.11	.57	.45	.45	.28
WMO06	.17	-.50	-.71	-.82	-.78	-.99	-.93
NUR	-.02	-.46	.01	-.13	-.31	-.21	.23
HN-ME	-.01	-.15	-.77	-.84	-.70	-.58	-.37
NDI	-.01	.26	.08	.26	.75	1.09	1.16
QUE	-.25	-.30	-.60	-.69	-1.74	-1.96	-2.25
STU	.08	-.31	-.28	-.65	-.46	-.85	-1.34
σσ	.941	1.074	1.284	1.366	1.470	1.536	1.666
σLS	.201	.478	.672	.766	1.072	1.168	1.286
σLS+E	.201	.408	.357	.357	.444	.304	.414

reduced significantly in the vicinity of the LONG SHOT explosion, which indicates that the LONG SHOT anomalies are estimating well the contrived anomalies; the improved locations for these events (Table XXII) bear this out. But all of the standard deviations with the step-off errors applied (σ_{LS+E}) compared to the σ_{LS} are also reduced but the location errors are not. This would indicate only that the contrived anomaly changes are being estimated well by the step-off process, but since the location errors remain identical to those obtained with the LONG SHOT anomalies, nothing is being gained except artificially low standard deviations.

The preceding exercise was made merely to demonstrate the futility of using a set of computed errors (residuals) from a network solution in an attempt to improve the location of a subsequent and nearby event. The reason this cannot work is that since the set of errors has a minimum value in a least-squares sense, and since the network is uniquely defined by the stations within it, the set of errors applied to some event already located in the region by that network has a mathematically null effect as far as further perturbations are concerned. Stepping-off slowly in this way across a broad region keeps this effect negligible, and the resultant locations remain the same as if no corrections were applied.

CONCLUSIONS

This study deals with travel-time anomalies, networks, and location consistencies from two viewpoints - real data and hypothetical data for Aleutian Islands events. The hypothetical data were used to validate some of the techniques employed on the real data. Physically, the technique of functionalizing and regionalizing the anomalies works well enough to justify further study and general applicability. No implication is made as to the ease with which it can be accomplished, but foremost among the criteria for using it is that the raw data set must be high quality; that is, the arrival times must read as unambiguously as possible. This usually involves a great deal of intrastation checking and interstation correlation. The earthquake signals from Aleutian Islands events are frequently subtly complicated: double events separated by 2-5 seconds, usually very different in magnitude; low amplitude first motions (which may be called precursors) not normally observed at noisier or low-magnification stations, etc. Since studies of anomalies and location techniques should not concern themselves with the ability of a seismic analyst to read seismograms correctly, the major effort of future studies must be to obtain as clean a data set as possible using all available techniques.

In using the real data for Aleutian Islands events, the complications introduced in the location stabilities are undoubtedly due in part to a depth effect. If the anomalies are caused by the integration of small imperfections in the earth model along a unique travel path (which is then related to a region/station description), there is good reason to expect the anomalies to be dissimilar when computed from two

events in the same region but at significantly different depths. It is not presently known what size of depth differences are to be considered significant, but the significance would probably depend on the particular stations used. However, before sensible studies can be made relevant to this depth effect, all possible efforts must be made to eliminate (1) arrival-time errors; (2) epicenter errors; (3) depth errors; and (4) network instabilities. To eliminate the first of these requires labor and patience. To eliminate the second may be impossible, except in the case of explosions or of using well-distributed local networks (<100 km epicentral distance). To eliminate the third requires the success of the first two plus the clear observation of pP. The fourth may be eliminated, or certainly be made manageable, by selection of suitable networks.

Neglecting depth effects, the analysis of the real and hypothetical data using various interpolation and adjustment schemes permits an estimate of resultant relative location error to be placed at 5-10 km throughout the Aleutian Islands for the seventeen events studied. The absolute location error is probably about the same, because LONG SHOT provides bias control in the vicinity of the Rat Islands and because all functional and regional anomalies were tied to LONG SHOT.

The regional anomalies finally determined for the Aleutian Islands yield consistent location patterns and least-squares time fits using four subsets of a fourteen station network.

That epicenters may be mislocated in the Aleutian Islands regions was demonstrated by taking various stable subsets of a 329-station network and the LONG SHOT explosion. The variable locations obtained, any of which could have been reported had LONG SHOT been an earthquake, produce a computed anomaly range at the teleseismic station NP-NT of more than 11.4 sec. This result

implicates epicenter mislocation as the chief cause of observed anomaly scatter.

Finally we have shown that arrival times in published bulletins are frequently in error by 1 second and more. The causes of these errors are probably: (1) missing first motion in complicated signals (such as double events), and (2) weak first motions (as at noisy stations). Any future studies of anomalies, networks, location accuracies, and earth models must begin with an analysis of raw seismograms in order to place any significance on the relation of anomalies or anomaly variations to physical processes.

REFERENCES

- Archambeau, C.B., Flinn, E.A. and Lambert, D.G., 1969, The fine structure of the upper mantle: Seismic Data Laboratory Report No. 232, Teledyne Geotech, Alexandria, Virginia.
- Chiburis, E.F., 1966, Relative travel-time anomalies at LASA and the location of epicenters using "shift": Seismic Data Laboratory Report No. 147, Teledyne Geotech, Alexandria, Virginia.
- Chiburis, E.F., 1968, Precision location of underground nuclear explosions using teleseismic networks and predetermined travel-time anomalies: Seismic Data Laboratory Report No. 214, Teledyne Geotech, Alexandria, Virginia.
- Chiburis, E.F. and Ahner, R.O., 1969, A location and travel-time study of Aleutian Islands explosions and earthquakes: Seismic Data Laboratory Report No. 239, Teledyne Geotech, Alexandria, Virginia.
- Chiburis, E.F. and Ahner, R.O., 1969, A location study of the Long Shot and Flexbag explosions and Aleutian Islands earthquakes: Seismic Data Laboratory Report No. 230, Teledyne Geotech, Alexandria, Virginia.
- Chiburis, E.F. and Ahner, R.O., 1969, The comparative detectability of pP at LASA, TFSO, UBSO and CPSO: Seismic Data Laboratory Report No. 231, Teledyne Geotech, Alexandria, Virginia.
- Chiburis, E.F. and Ahner, R.O., 1970, A Seismic location study of station anomalies, network effects, and regional bias at the Nevada Test Site: Seismic Data Laboratory Report No. 253, Teledyne Geotech, Alexandria, Virginia.
- Chiburis, E.F. and Dean, W.C., 1965, Teleseismic signal alignment at the Tonto Forest extended array: Seismic Data Laboratory Report No. 125, Teledyne Geotech, Alexandria, Virginia.

REFERENCES (Cont'd.)

- Huntsberger, D.V., 1961, Elements of statistical inference, p. 264 ff: Boston, Allyn and Bacon, Inc.
- Kos, D.W. and Kennedy, J.E., 1969, Development of a system to deliver and detonate large explosive charges undersea: IIT Research Institute Report No. D7034-25, January.
- Lambert, D.G., Von Seggern, D.H., Alexander, S.S., and Galat, G.A., 1969, The Long Shot experiment, Vol. I, Basic observations and measurements; the Long Shot experiment, Vol. II, Comprehensive analysis: Seismic Data Laboratory Report No. 234, Teledyne Geotech, Alexandria, Virginia.
- Lilwall, R.C. and Douglas, A., 1969, The quest for a P travel-time standard: Nature, v. 222, p. 975-977, June 7.